TR/BR-1/98-99

APPLICATION OF GIUH AND GIS BASED APPROACH FOR DESIGN FLOOD ESTIMATION

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1997-98

PREFACE

Estimation of design flood for hydrological design of various water resources structures, particularly for medium and major water resources schemes, has been one of the most active areas of research for the hydrologists and water resources engineers. Geomorphological Instantaneous Unit Hydrographs (GIUH) have been proposed by several engineers as a tool to simulate runoff hydrographs from rainfall for ungauged catchments.

The important geomorphological parameters which represent the linear, areal and slope aspects of the catchement are required to be evaluated either from toposheets or from other indirect means. Application of GIS package provides an effiecient and accurate means for the evaluation of these characteristics. Efforts have been made by many investigators to provide linkage between the response function in the form of instantaneous unit hydrograph (IUH) and the various geomorphological characteristics. This approach is termed as the GIUH approach. Many conceptual models for IUH derivation are available and number of attempts have been made to derive the parameters of these models using geomorphological and climatological characteristics.

A mathematical model has been developed at the National Institute of Hydrology, which enables the evaluation of the Clark Model parameter, which is a conceptual model for IUH derivation using geomorphological characteristics of the basin. Earlier this model was successfully applied for the simulation of historical flood events in Kolar sub-basin, Upper Narmda and Tapi sub-zone 3-c. In this study, the applicability of estimation has been illustrated using data of four dam catchments namely Jawai, Sei, Gamabhiri and Alnia which form part of Luni and Chambal basins in Rajasthan.

This study has been carried out by Shri Sanjay K. Jain, Scientist 'C' with the assistance given by Mr. Rajesh Nema and Mr. Pankaj Garg, SRA under the guidance of Dr. S.M.Seth, Director and Shri R.D.Singh, Scientist 'E'. It is hoped that the study will provide basic understanding about the methodology which would be useful for the hydrologists and field engineers for the estimation of design flood using GIUH based Clark model.

(S.M.Seth)

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ABSTRACT

Quantitative understanding and prediction of the processes of runoff generation and its transmission to the outlet represent one of the most basic and challenging areas of hydrology. Unit hydrograph techniques have been widely applied for the estimation of design flood hydrograph at the site of interest. Whenever adequate rainfall-runoff records are available, unit hydrograph for that catchment can be developed very easily analysing the available records. For ungauged catchments, unit hydrograph may be derived using either regional unit hydrograph approach or alternatively GIUH approach. The Geomorhological Instantaneous Unit Hydrograph (GIUH) approach may be applied for the simulation of flood events particularly fr the ungauged catchments.

The objective of the present study is to apply GIUH and GIS based approach for the estimation of design flood. For this purpose the design storm data of four dam catchments alongwith morphological characteristics are considered. In this study the geomorphological parameters and time area diagrams for each dam catchments were generated using Geographic Information System (GIS) package ILWIS (Integrated Land and Water Information System). The geopmorphological parameters together with time-area diagramme forms important input for the GIUH based Clark model. This model has been applied for deriving the instantaneous unit hydrograph and thereby for estimation of design flood in four dam catchments located in Rajasthan viz. Jawai, Sei, Gamabhiri and Alnia, which are part of Luni and Chambal basins. A review of the previous studies carried out using GIUH approach has been presented. Further more a review is also presented for the studies carried out using GIS techniques.

The design flood estimates have been obtained for different scenarios of the design storm. These design flood estimates have been compared with the available design flood estimates in order to examine the applicability of the above approach. It was found that the velocity is one of the important design parameters. Its estimation for design condition is one of the most crucial issues, which require further investigation.

1.0 INTRODUCTION

Modelling of rainfall - runoff process on catchment scale has been one of the most active areas of research in hydrology. In order to estimate the design flood or formulate real time flood forecast for small catchments, hydrological models capable of simulating the response of historical flood events are needed. Whenever catchments are gauged event based models may be developed, which may be calibrated and validated for the historical flood events. Unfortunately, small catchments are large in number and most of them are ungauged. Therefore, it would not be possible to calibrate and validate the event-based models in absence of flow data for the ungauged catchments. One of the most popular approaches for the simulation of flood hydrograph for the ungauged catchments is based on the application of the developed regional unit hydrograph utilising the rainfall - runoff records of the gauged catchments. However, this approach has somewhat limited scope since the hydrological behaviour of many nearby catchments have to be ascertained for establishing the regional formula for the unit hydrograph parameters. The second approach, which may be utilised for developing the unit hydrograph for ungauged catchments, utilises geomorphological characteristics. This approach has many advantages over the regionalisation approach as it avoids the requirement of data and computations in the neighbouring gauged catchments in the region.

A river basin is made up of two interrelated systems: the channel network and the hillslopes. The hillslopes control the production of storm water runoff which, in turn, is transported through the channel netork toward the basin outlet. The runoff-contributing areas of the gill-slopes are both a cause and an effect of the drainage network growth and development. There is certainly a link between geomorphologic laws and hydrologic response and this need some measure of description of a basin. The description used here is the instantaneous unit hydrograph (IUH) that is equivalent to the unit impulse response function of the basin. The objective is then to explicitly derive the IUH through its connection with the most basic and general laws describing the architecture of the drainage

network, which are the so-called Horton's laws of basin composition. The resulting response function is what is called the geomorphologic instantaneous unit hydrograph or GIUH.

The Strahler ordering procedure can be summarized as follows:

- Channels that originate at a source are defined to be first-order streams.
- When two streams of order ω join, a stream of order ω +1 is created.
- When two streams of different order join, the channel segment immediately downstream has the higher of the orders of the two combining streams.

The quantitative expressions of Horton's laws are :

Laws of stream numbers

$N\omega/N\omega+1 = R_B$

Laws of stream length

$L\omega/L\omega+1 = R_L$

Laws of stream areas

$A\omega/A\omega+1 = R_A$

Where $N\omega$ is the number of streams of order ω , Where $L\omega$ is the mean length of the streams of order ω and $A\omega$ is the mean area of the basins of order ω, R_B, R_L and R_A represent the bifurcation ratio, the length ration and the area ratio whose values in nature are normally between 3 and 5 for R_B, between 1.5 and 3.5 for R_L and between 3 and 6 for R_A

In GIUH based approach, a unifying synthesis of the hydrological response of a catchment to surface runoff is attempted by linking the instantaneous unit hydrograph (IUH) with the geomorphological parameters of a basin. Equations of general character are derived which express the IUH as a function of Horton's numbers i.e. area ratio (R_a), bifurcation ratio (R_b) and length ratio (R_l) (Strahler, 1957); an internal scale parameter L_W denoting the length of highest order stream; and the peak velocity of streamflow V expected during the storm. The IUH is time varying in character for different storms.

The geomorphological theory of unit hydrograph (GIUH) was originated by Rodriguez-Iturbe and Valdes (1979), who rationally interpreted the runoff hydrograph in the framework of travel time distribution explicitly accounting for geomorphological structure of a basin. They have derived the basic equations for the GIUH of a third-order basin. The

equations for higher-order can be derived with exactly the same framework. However, for basins of any order the peak q_{pg} and the time to peak t_{pg} , which are the most important characteristics of the GIUH, are worked out from the derived functional relationship of the GIUH as:

$$q_{pg} = 1.31 \quad R_L^{0.43} \left(\frac{V}{L_\Omega} \right) \qquad \text{...........(1)}$$

$$t_{pg} = 0.44 \quad R_L^{-0.38} \left(\frac{R_B}{R_A} \right)^{0.55} \left(\frac{L_\Omega}{V} \right) \qquad \text{...........(2)}$$

The above equations represent general relationships which allow the estimation of the peak and time to peak of the IUH for any watershed.

On multiplying Eq.(1) and Eq.(2) we get a non-dimensional term $q_{pg} * t_{pg}$ as:

$$q_{pg} * t_{pg} = 0.5764 \quad \left(\frac{R_B}{R_A} \right)^{0.55} \left(R_L \right)^{0.05} \qquad \text{.........(3)}$$

This term is not dependent upon the velocity and thereby on the storm characteristics and hence is a function of only the catchment characteristics.

For the dynamic parameter velocity (V), Rodriquez et al. (1979) in their studies assumed that the flow velocity at any given moment during the storm can be taken as constant throughout the basin. The characteristic velocity for the basin as a whole changes throughout as the storm progresses. For the derivation of GIUH, this can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin. However, for ungauged catchments the peak discharge is not known and so this criterion for estimation of velocity cannot be applied. In such a situation one possible approach could be estimation of velocity by using the relationship developed between the velocity and the rainfall excess intensity.

One advantage of the geomorphological instantaneous unit hydrograph (GIUH) approach is the potential of deriving the UH using only the information obtainable from topographic maps or remote sensing, possibly linked with geographic information system (GIS) and digital elevation model (DEM). The input to a GIS may be remotely sensed data, digital models of the terrain, or point or aerial data compiled in the forms of maps, tables or reports. GIS provide a digital representation of watershed characterisation used in hydrologic modelling. Hydrologic applications of GIS have ranged from synthesis and characterization of hydrologic tendencies to prediction of response to hydrologic events (Tao and Kouwen,1989). A GIS can provide the basis for hydrologic modelling of ungauged catchments and for studying the hydrologic impact of physical changes within a catchment. The integration of GIS into hydrologic models follows one of the two approaches (i) to develop hydrologic models that operate within a GIS framework (Moore et al.,1987),(ii) to develop GIS techniques that partially parameterize existing hydrologic models (Deroo et al.1989).

Conceptual modelling approach for the derivation of instantaneous unit hydrograph (IUH) is a parametric approach. Clark model is a conceptual model for the derivation of IUH. A hybrid approach which combines the Clark Model with the geomorphological instantaneous unit hydrograph approach, is used in the present study for the simulation of the flood hydrograph for the small to medium sized dam catchments of Rajasthan. It provides a procedure for the estimation of parameters of the conceptual model of IUH without taking up the tedious regionalisation process. In this approach a simple procedure for estimation of velocity using the channel cross-section, channel roughness and the storm characteristics is considered. However, for the present study the information available for velocity estimation was not adequate. Hence a reasonable estimate for velocity has been assumed based on the information available for the neighbouring catchments for the design storm condition. Various design storm patterns are assumed and design flood estimates for each storm patterns are obtained.

2.0 REVIEW OF LITERATURE

Quantitative understanding and prediction of the processes of runoff generation and its transmission to the outlet represent one of the most basic and challenging areas of scientific hydrology. The simplest theory for runoff computation is through multiplication of rainfall with some factor called as the runoff coefficient. A better way to transform rainfall into runoff is to apply conceptual models in which the various interrelated hydrological processes are conceptualized.

Most of the models are generally calibrated based on the analysis of rainfall-runoff data for gauged catchments. However, these models can not be calibrated for those catchments, which lack such data. Consequently, the parameters of those models for ungauged catchments may be determined from the regional relationships developed by correlating the model parameters with physically measurable catchment characteristics of the gauged catchments. Optimization is one of the most widely used techniques available to calibrate the model for gauged catchments. Frequently the model parameters are optimised for some selected rainfall-runoff events over a given watershed, using a suitable optimization procedure. The optimized parameter values are then utilized in the model to predict runoff for the rainfall events of interest not used in the optimization. This approach is obviously not applicable to ungauged watersheds. Further, it has other shortcomings as the optimized parameters can best represent the watershed only for the events used in the optimization. The optimized values change with the change in the event. Also, the extensive amount of data required for optimization is normally lacking and thus proves prohibitive in the widespread use of model applicability.

The other approach attempts to establish relationships between model parameters and physically measurable watershed characteristics. These relationships are then assumed to hold for ungauged watersheds having similar hydrologic characteristics. Rainfall-runoff relationships for ungauged watersheds have been developed along two complimentary lines: (I) Empirical equations have been developed to relate some individual runoff hydrograph characteristics to watershed characteristics (2) Procedures have been developed to synthesize the entire runoff hydrograph from watershed characteristics. In this direction several investigators have worked towards developing an Instantaneous Unit Hydrograh (IUH) from the geomorphology of catchments as derived

from readily available topographic maps. A majority of the past studies have been used conceptual and synthetic unit hydrograph models. Some of the important studies carried out by different investigators are described as follows:

Benard(1935) accomplished the transformation of rainfall to runoff through the medium of a distribution graph, which was also a function of catchment characteristics. He assumed that the peak of the unit hydrograpph was inversely proportional to the time of concentration, given by the length of longest channel divided by the square root of the catchment average slope. McCarthy (1938) and Synder (1938) correlated the unit hydrograph and the topographic parameters such as area, overland slope, and stream pattern to permit an estimate of the unit hydrograph parameters of an ungauged catchment. Clark(1945) suggested that the ordinates of the IUH should be proportional to the derivatives of the time-area concentration tc, a storage attenuation coefficient R, and a time area diagram for the catchment.

Taylor and Schwarz (1952) related the lag and peak flow values of the unit hydrograph with the catchment characteristics and duration of rainfall excess empirically. They found that the peak of IUH was a function of main channel slope and the shape of IUH was a function of catchment length. Minshal (1960) pointed out that peak flow and time to peak of the unit hydrogrph were dependent upon rainfall intensity and storm pattern. He presented an empirical method of constructing a synthetic unit hydrograph for small catchment by relating the percentage of peak flow before and after peak flow with rainfall intensity and drainage area.

Nash (1960) related the first and second moments of IUH with important physical characteristics for some English catchments. The relationships finally obtained were

$$m_1 = 27.6\,A^{0.03}\,S^{0.3}$$

$$m_2 = 1.0\,m1^{0.2}\,S^{-0.1}$$

Where m1 and m2 are the first and second moment of IUH about the origin; A= catchment area 9 in sq. mi); and S is the overland slope.

National Institute of Hydrology (1985) has carried out a regional unit hydrograph study for Narmada basin based on Clark's approach. In this study the parameters of the Clark model have been derived for each of the sub-basin of Narmada basin using HEC-I package. A regional relationship has been developed in the graphical form relating average value of (t + R) for each sub-basin with their respective catchment area. A regional value of R/(t + R) along with the graphical relationship has been used to estimate the parameters of the Clark model for ungauged catchment of the Narmada basin.

Huq. et.al. (1982) developed synthetic unit hydrograph relationships using the data of the catchments in Gangetic plains, Mahanadi basin, Krishna basin and Bhramaputra basin. These relationships have been developed relating the parameters of the representative unit hydrograph for gauged catchment with a suitable combination of the physical characteristics of the catchment using regression analysis.

Boyd (1978, 1982) developed the linear watershed bounded network (LWBN) model for synthesis of the IUH employing geomorphologic and hydrologic properties of the watershed. The model divides a watershed into sub-areas bounded by watershed lines using large-scale topographic maps. The model has a large number of lumped storage parameters. Most of these parameters are deduced from geomorphologic properties.

Mathur and Vijay Kumar (1987) related the physical parameters of twenty small and medium catchments in order to arrive at the most effective combination of the physical parameters for the development of the regional unit hydrograph relationships.

Up to this nobody actually used the concept of GIUH, in fact Rodriguez-Itrube and Valedas (1979) introduced the concept of the GIUH by linking the IUH peak discharge qp and time to peak tp with the geomorphologic parameters of the catchment and a dynamic parameter (velocity, v). After this several investigators worked on this concept and also some of them related the work with GIS. The advantage of the GIUH approach is the potential of deriving the UH using only the information obtainable from topographic maps or remote sensing, possibly linked with GIS and DEM. The work using GIUH based approach and linking of models with GIS with GIUH based models in GIS in particular.

The geomorphological theory of the GIUH was originated by Rodriguez and Valdes (1979) who rationally interpreted the runoff hydrograph in the framework of travle time distribution explicitly accounting for the geomorphological structure of a fluvial basin. Although the theory has a few ancestors, particularly the definition of isochrones of travel times implied by the time area diagrams (e.g. Dooge, 1973), the dynamic rescaling of the width functions (Kirby, 1976) etc. Rodriguez and Valdes attempted a unifying synthesis of the hydrologic response of a catchment to surface runoff by linking the instantaneous unit hydrograph (IUH) with the geomorphologic parameters of a basin. Equations of general character were derived which express the IUH as a function of Horton's numbers R_a,R_b and R_l ; an internal scale parameter L_Ω and a mean velocity of streamflow v. Rodriguez-Iturbe and his associates have since extended this approach by explicitly incorporating climatic characteristics and have studied several aspects including hydrologic similarity.

Gupta, Waymire and C.T.Wang (1980) examined this approach, and reformulated, simplified and made it more general. Two examples were developed which lead to explicit formulae for the IUH. These examples were formally analogous to the solutions that would result if a basin were represented in terms of linear reservoirs and channels, respectively, in series and in parallel.

Panigrahi (1991) estimated the velocity using the Manning's equation. The methodology involves the estimation of equilibrium discharges and subsequently the estimation of the velocity corresponding to it using Manning's equation. It requires the intensity of each rainfall block for the event for the computation of equilibrium discharge. The channel cross-section at the gauging site, longitudinal slope and Manning's roughness are also required during the computation of the velocity. The methodology has been allied to estimate the velocity to derive the Nash model parameters using GIUH approach for the Kolar sub-basin of Narmada basin.

Yen et al. (1997) presented the GIUH approach by applying this on two hilly watersheds in the eastern United States and two relatively flat slope watersheds in Illiniois. Comparison between the simulated and observed hydrographs for a number of rainstorms indicated the potential 7de l as a useful tool in watershed rainfall-runoff analysis.

Lee et al. (1997) emphasized on the difficulty in the determination of travel time, which is actually a hydraulic problem. They used the kinamatic wave theory to analytically determine the travel times for overland and channel flows in a stream ordering subbasin system. According this study the resultant instantaneous unit hydrograph is a function of the time rate of water input (intensity of rainfall excess in application); hence the linearity restriction of the unit hydrograph theory is relaxed.

Bhaskar et al. (1997) derived the GIUH from watershed geomorphological characteristics and is then related to the parameters of the GIUH and the Nash IUH model. They carried out runoff modelling using GIUH and ARC/INFO GIS for twelve watersheds in the big sandy river basin in eastern Kentucky. The required data base for these watersheds were compiled using a GIS software ARC/INFO. The hydrological model used to simulate watershed runoff was a geomorphic model called as watershed hydrology simulation (WAHS) model. This model simulates runoff from a watershed by developing a deterministic form of the GIUH based on a concepualization of the watershed channel network in conjunction with the Strahler's stream-ordering system.

Rose et al. (1997) used digital elevation model data for the derivation of the geomorphological instantaneous unit hydrograph for three-mountain basin in Italian Alps. Two different probabilistic models were used and they both relate the characteristic response function of the basin to its DEM data derived networks: one is derived assuming Strahler stream ordering system and the other by averaging a flow equation with respect to the network structure. A sensitivity analysis was also performed to study the influence of the variability of morphometric property, with respect to threshold area, on the hydrological response obtained.

Lee K.T. (1998) generated design hydrographs by DEM assisted geomorphic runoff simulation. In this study to simplify the time-consuming work involved in geomorphic parameter measurement on topographic maps, the GIUH model is linked with GIS to obtain geomorphic parameters from DEM. In this work, a case study performed for peak flow analysis in an ungauged watershed is presented. The design storm was applied to the geomorphic runoff simulation model to obtain the design hydrograph.

Development of GIUH has potential applications for the estimation of runoff, flood forecasting and design flood estimation, particularly for the ungauged catchments or for the catchments with limited data. Most of the studies available in literature regarding the GIUH approach are synthetic in nature and are in the early stages of research and development. Very few studies are available where its practical applications have been demonstrated. As GIUH approach has many advantages over the traditional method of developing the regional unit hydrograph for the simulation of flood events in the ungauged catchment, it would be appropriate to verify the application of GIUH approach for simulating the flood response of a gauged catchment. In the light of this a new approach of rainfall-runoff modelling based on the geomorphological characteristics has been developed at the National Institute of Hydrology. Since in India the use of Clark model has been recommended for the derivation of unit hydrograph, therefore, Clark model has been considered out of various conceptual events based models. In this approach, the parameters of the Clark model have been estimated using the geomorphological characteristics. This approach was tested satisfactorily on the Kolar sub-basin of river Narmada (NIH,1993).

Choudhry at al. (1995) applied hybrid approach for there small bridge catchments of Upper Narmada & Tapi sub zone. The developed technique links the GIUH equations derived by Rodriquez and the parameters of the Clark model. It enables the estimation of parameters of Clark model using the geomorphological characteristics, hydraulic properties of the main stream and storm characteristics.

In the present study this approach is applied for four dam catchments located in Rajasthan and also use of GIS technique is made for derivation some of the parameters related with catchment characteristics, required for the model.

3.0 THE STATEMENT OF PROBLEM

GIUH based approach, a unifying synthesis of the hydrological response of a catchment to surface runoff is attempted by linking the instantaneous unit hydrograph (IUH) with the geomorphological parameters of a basin. Equations of general character are derived which express the IUH as a function of Horton's numbers i.e. area ratio (R_a), bifurcation ratio (R_b) and length ratio (R_l) (Strahler, 1957); an internal scale parameter L_W denoting the length of highest order stream; and the peak velocity of streamflow V expected during the storm. The IUH is time varying in character for different storms. The geomorphological theory of unit hydrograph (GIUH) was originated by Rodriguez-Iturbe and Valdes (1979), who rationally interpreted the runoff hydrograph in the framework of travel time distribution explicitly accounting for geopmorphological structure of a basin.

A new approach of rainfall-runoff modelling has been developed at the National Institute of Hydrology (NIH, 1993) in which the conceptual modelling has been clubbed with the GIUH approach. This has enabled to determine the complete shape of the IUH by using the formulae given for the peak characteristics of the GIUH. Simultaneously on the other hand, it has been possible to use the conceptual modelling approach without even required to calibrate its parameters on the basis of the observed runoff data. The conceptual model used in this new approach is the Clark model.

In this study the main objectives are

- ✓ To derive the geomorphological characteristics using ILWIS GIS software
- ✓ To develop DEM using contour data from Survey of India toposheets on the scale of 1:50,00
- ✓ To develop the time-area diagram using the data of DEM
- ✓ To derive time varying IUH using geomorphological characteristics for the estimation of the design flood
- ✓ To derive the design storm using the different methods of critical time sequencing
- ✓ To estimate the design flood corresponding to each design storm pattern

In order to achieve the above objectives the study has been carried out for four dam catchments located in Rajasthan viz. Jawai , Sei, Alnia and Gamabhiri dam catchments.

4.0 THE STUDY AREA AND DATA AVAILABILITY

For the present work four dams catchments located in Rajasthan, India were selected. The dam catchments included in the present study are Jawai, Sei, and Gambhiri and Alnia dam catchments. The rivers on which these dams are constructed are the tributaries of Luni and Chambal rivers. The description of each dam catchment is given below.

The Central Water Commission of India has divided the country into 7 major zones which in turn are subdivided on the basis of river basins and sub basins into 26 hydro-meteorologically homogeneous subzones of moderate sizes (CWC, 1983). The study areas chosen for this study falls into Chambal and Luni subzone nos 1(a) and 1(b) respectively.

4.1 THE STUDY AREA

4.1.1 Jawai Dam Catchment

The Jawai dam was constructed across the river Jawai,a tributary of river Luni which flows in Rajasthan. The dam is situated at Longitude 73° 9' 40" and Latitude 25° 6' 10" , the catchment area is 720 sq. km. and the shape of the basin is fan shaped. The topography of the river basin is undulating with altitude varying between 300m and 1100 m. The climate is semi arid with large variation in temperature. The area is influenced with southwest monsoon. The mean annual rainfall is about 500 mm ,90% of which occurs during June to September months. The annual rainfall varies from year to year and region has experienced a few major rainstorms.

4.1.2 Sei Dam Catchment

For this study, the catchment of Sei dam located at 24^0 23' 0"(Lat.) and 73^0 11' 8"(Long.) on Sei river of Sabarmati basin in Mahi & Sabarmati subzone (Subzone 3a) has been chosen. The Sei diversion and storage dam project was started in the year 1969 and it completed in the year 1977. This diversion dam has been built to harness water of river Sei originating from slopes of Aravali hills and to divert the water to a nearby Jawai dam. The total catchment of Sei river, which is a tributary of Sabarmati at dam site, is 320 sq. km. The

area is mostly hilly with steep slopes towards the river. The average rainfall in the catchment area is 675 mm.

4.1.3 Gambhiri Dam Catchment

Gambhiri river is a small tributary of the Berach/Banas river of the Chambal basin. The river rises in Madhaya Pradesh and travelling for a length of about 83 km in the North West direction joins the Berach river downstream of Chittorgarh town. The Gambhiri river is joined by its important tributary, Daru nadi near the Gambhiri dam site.

The topography of the river basin is undulating with altitude varying between 600 m and 300 m. According the soil classification, the soil is mixed red and black soil. The catchment is covered with grass land and scrub.

The Gambhiri basin lies in southern Rajasthan. Its climate is semi-arid with large variations in temperature. The region is influenced by south-west monsoon. The rainfall is received by dissipation of the remnants of the Bay of Bengal cyclones and occasional Arbian sea rainstorms passing over the region. The mean annual rainfall is about 750 mm, 90 % of which occurs in the months of June to September. The annual rainfall varies widely from year to year. Even though the region is located in semi-arid region far away from the Bay of Bengal, the region has experienced some of the major rainstorms.

4.1.4 Alnia Dam Catchment

Alnia river is a small tributary of the Chambal river. It originates from Mukandanwara and traversing a length of 60.0 km joins the Chambal river about 24.0 km downstream of Kota barrage site. A number of streams join the Alnia river before it joins the Chambal river. The shape of the catchment up to the dam site is fan shaped. The type of soil is alluvial.

The Alnia drainage basin is located in the Chambal basin in eastern Rajasthan. Climatological the area is semi arid with large variations in temperature and rainfall. The region is influenced by the south east monsoon (June to September). The mean annual rainfall over the drainage basin is 800 mm. The annual rainfall varies widely from year to year. Even though the area is located in the semi-arid region far away from the Bay of Bengal , the region has experienced some of the worst rainstorms during the last 100 years. During

17-19 July 1981 rainstorm, the total point rainfall was more than 900 mm at Kota rain gauge near Jaipur.

The Alnia dam has been constructed on Alnia river at latitude 25 ^{0} N and longitude 75 ^{0} 53' near Simpura village, Tehsil Ladpura, district Kota.

4.2 TOPOGRAPHIC DATA

The topographic maps of dam catchments viz Jawai, Sei, Gambhiri and Alnia located in Rajasthan are prepared using Survey of India toposheets at a scale of 1:50,000. The toposheets nos are 45 G/4 & 8, 45 H/1,2 & 5 for Jawai dam catchment, 45 H/2,5 & 6 for Sei dam catchment, 45 I/10,14,15 for Gambhiri dam catchment and 45 O/16 and 45 P/13 for Alnia dam catchment.

4.3 STORM DATA

For the present study area as such no rainfall/discharge data was available. Therefore Probable Maximum Precipitation (PMP) was taken from the report ' Safety evaluation and remedial works to enhance safety status of dams prepared by Consultancy Engineering Services (India) private Limited (1994). In that report for each catchment PMP was distributed in a smaller time interval of 2 hour. For each catchment the distribution of rainfall was taken from the report.

4.3.1 Jawai dam Catchment

PMP depth of 48.0 cm is the total of 24 hours. This depth was split into smaller time intervals equaling the unit period adopted for the unit hydrograph. In the report the unit period taken was 2 hours. Further the rainfall excess increments during PMP have been computed assuming a loss rate of 3.0 mm/hr. The rate has been fixed by trials such that the storm runoff to rainfall ratio is about 85 %. The 2-hourly increments of 24 hour PMP value of 48.0 cm is given in the following table no. 4.1.

Table 4.1 : 2-hour distribution of 24 hour PMP value (Jawai dam catchment)

Time (hr)	Rainfall increments (cm)	Loss rate @ 3.0mm/hr (cm)	Rainfall-excess increments (cm)
2	11.04	0.6	10.44
4	6.24	0.6	5.64
6	5.28	0.6	4.68
8	3.84	0.6	3.24
10	3.84	0.6	3.24
12	2.88	0.6	2.28
14	2.88	0.6	2.28
16	2.88	0.6	2.28
18	2.88	0.6	2.28
20	1.92	0.6	1.32
22	1.92	0.6	1.32
24	2.4	0.6	1.8
Total	48.0	7.20	40.80

4.3.2 Gambhiri dam catchment

PMP depth of 53.5 cm is the total of 24 hours. For the computation of design flood discharge the 24-hour depth value has to be split into smaller time intervals and given below in the table no. 4.2.

Table 4.2 : 2 hour distribution of 24 hour PMP value (Gambhiri dam catchment)

Time (hr)	Rainfall increments (cm)	Loss rate @ 3.0mm/hr (cm)	Rainfall-excess increments (cm)
2	12.31	0.6	11.71
4	6.95	0.6	6.35
6	5.89	0.6	5.29
8	4.28	0.6	3.68
10	4.28	0.6	3.68
12	3.21	0.6	2.61

14	3.21	0.6	2.61
16	3.21	0.6	2.61
18	3.21	0.6	2.61
20	2.14	0.6	1.54
22	2.14	0.6	1.54
24	2.67	0.6	2.07
Total	53.5	7.20	46.3

4.3.3 Alnia dam catchment

The rainfall excess increments at 1-hourly intervals have been computed assuming a uniform loss rate of 4.00 mm/hr and are presented in the table no. 4.3.

Table 4.3 Hourly distribution of PMP value (Alnia dam catchment)

Time (hr)	Rainfall increments (cm)	Loss rate @ 4.00 mm/hr (cm)	Rainfall-excess increments (cm)
1	20.52	0.4	20.12
2	9.43	0.4	9.03
3	7.21	0.4	6.81
4	4.99	0.4	4.59
5	4.44	0.4	4.40
6	2.21	0.4	1.81
7	2.22	0.4	1.81
8	1.11	0.4	0.71
9	1.11	0.4	0.71
10	0.56	0.4	0.16
11	0.55	0.4	0.15
12	1.11	0.4	0.71
Total	55.46	4.80	50.66

4.3.4 Sei dam catchment

The rainfall excess increments at 1-hourly intervals have been computed assuming a uniform loss rate of 4.5 mm/hr and are presented in the table no. 4.4.

Table 4.4 Hourly distribution of PMP value (Sei dam catchment)

Time (hr)	Rainfall increments (cm)	Loss rate @ 4.50 mm/hr (cm)	Rainfall-excess increments (cm)
1	13.71	0.45	13.26
2	6.61	0.45	6.16
3	5.67	0.45	5.22
4	3.31	0.45	2.86
5	2.84	0.45	2.39
6	3.31	0.45	2.86
7	1.89	0.45	1.44
8	1.89	0.45	1.44
9	1.89	0.45	1.44
10	0.47	0.45	1.44
11	1.89	0.45	0.02
12	0.47	0.45	1.44
13	0.48	0.45	0.02
14	0.94	0.45	0.03
15	1.11	0.45	0.49
Total			

4.4 Unit Hydrograph

There was no gauge and discharge site in the basin near the dam site. The unit hydrograph as taken into the report prepared by CES Ltd. was taken for this study. The procedure followed for the preparation of this unit hydrograph is described below:

Central Water Commission (Directorate of small catchment) had prepared in December 1988 ' Flood estimation report for Chambal sub zone- 1(b). In this study, regional correlationships have developed such that 1-hour unit hydrograh parameters for an ungauged basin can be determined from catchment characteristics. It has been mentioned in the report that the methodology is applicable to catchments areas ranging from 25.0 to 2500.0 sq. km. Though Jawai dam catchment lies in the Luni basin, its catchment characteristics are similar to those of the Chambal basin and it is considered that

correlation equations of 1-hour unit hydrograph parameters developed for the Chambal sub-basin would be applicable to the Jawai dam also. The parameters of 1-hour Unit hydrograph are taken as follows:

$$t_p = 0.339(L/\sqrt{s})^{0.826}$$

$$T_p = t_p + 0.5$$

$$q_p = 1.251(t_p)^{-0.61}$$

$$Q_p = q_p x A$$

$$T_B = 6.622(t_p)^{0.617}$$

$$W_{50} = (2.215 q_p)^{-1.034}$$

$$W_{75} = 1.191(q_p)$$

$$WR_{50} = 0.834(q_p)^{-1.077}$$

$$WR_{75} = 0.502(q_p)^{-1.065}$$

The procedure followed for unit hydrograph preparation for Gambhiri and Alnia dam catchments are also same as given for Jawai dam catchment.

However for Sei dam catchment the relationship for derivation of the parameters is little bit different and given below

$$t_p = 0.339(L/\sqrt{s})^{0.826}$$

$$T_p = t_p + 0.5$$

$$q_p = 1.251(t_p)^{-0.61}$$

$$Q_p = q_p x A$$

$$T_B = 6.622(t_p)^{0.617}$$

$$W_{50} = (2.215 q_p)^{-1.034}$$

$$W_{75} = 1.191(q_p)$$

$$WR_{50} = 0.834(q_p)^{-1.077}$$

$$WR_{75} = 0.502(q_p)^{-1.065}$$

The unit hydrograph discharges at 1-hour intervals for all the dam catchments are given in the table no. 4.5.

Table 4.5 : Unit Hydrograph for all the catchments

Time (hr.)	1- hour UH discharge (Cumecs)			
	Jawai	Sei	Gambhiri	Alnia
1	27.5	27.5	27.5	27.5
2	62.5	62.5	62.5	62.5
3	105.0	105.0	105.0	105.0
4	160.0	160.0	160.0	160.0
5	257.5	257.5	257.5	257.5
6	320.0	320.0	320.0	320.0
7	275.0	275.0	275.0	275.0
8	220.0	220.0	220.0	220.0
9	127.0	127.0	127.0	127.0
10	92.5	92.5	92.5	92.5
11	62.5	62.5	62.5	62.5
12	45.0	45.0	45.0	45.0
13	32.5	32.5	32.5	32.5
14	20.0	20.0	20.0	20.0
15	12.5	12.5	12.5	12.5
16	7.5	7.5	7.5	7.5
17	3.8	3.8	3.8	3.8
18	0	0	0	0

5.0 METHODOLOGY

In this study, the peak characteristics of the IUH as obtained in Eqs. (1) & (2) (Chapter1) are utilised for the evaluation of Clark model parameters. Once the parameters of this GIUH based Clark model are known, the complete IUH may be derived. The different parameters developed using field data and GIS are explained in the following sections.

5.1 PREPARATION OF DATA BASE IN ILWIS

The GIS software used in the present study is Integrated Land and Water Information System (ILWIS). ILWIS stands for Integrated Land and Water Information System. It was developed at ITC, Enschede, The Netherlands. ILWIS is a GIS that integrates image processing capabilities, tabular data bases and conventional GIS characteristics. Data acquisition from aerospace images, an integral part of the system, enables effective monitoring. This is important in regions in which data is scarce or difficult to gather. The conceptualization of the system takes into account that not all GIS users have a thorough knowledge of computers.

A conversion program allows the importation of the remote sensing data, tabular data, raster maps and vector files in several other formats. Analog data can be transformed into vector format by means of a digitizing program, of which on screen digitizing, with any raster map of image as on screen underlay is one of the most important feature.

Complex modelling of features can be executed by the 'Map Calculator'. The map calculator includes an easy to use modelling language and the possibility of using mathematical functions and macros. It integrates tabular and spatial databases. Complex procedures can be executed rapidly on portions of study area on the video memory. After evaluation and assessment of results, the procedure can be applied to the entire area. Tabular and spatial data bases can be used independently and on an integrated bases. Calculations, queries and simple statistical analysis can be performed by the Table Calculator. Computational procedures and efficient use of system are improved by the appropriate use of modelling processes. Fast overlay procedures constitute one of the main characteristic of the system.

Image processing capabilities integrated with spatial modelling and tabular data bases constitute a powerful tool. Together they enable a kind of analysis which was not possible until recently. ILWIS also incorporates conventional image processing techniques such as filtering, geometric corrections and classification procedures. Special features of interpolation of point data and contour lines are also available to create DEMs (Digital Elevation Models). Special filters and functions are available to produce slope and aspect maps.

Data processing several basic image analysis capabilities, such as histogram manipulation, automatic stretch display, user defined filters, transfer function manipulation and other standard functions. It includes calculation of covariance and correlation matrices, eigen values and eigenvectors and other statistics. A user friendly sampling program allows sampling by pixel, feature space plot analysis and sample and class statistics. Several classifier algorithms can be used. Before classifying an entire image, the behaviour of the different classifiers can be compared through an interactive pixel classification routine.

The ILWIS menu is subdivided in several modules and submodules. A brief description of the functioality of the modules, sub-modules and menu options is given. There is not always a one-to-one relationship between menu options and program names and that some menu options can be found in different modules. There are six main modules namely Input, Vector, Raster, Tables, Output and Command. These modules are described below:

The boundary of all the four catchment and all the streams have been mapped at a scale of 1:50,000 from Survey of India toposheets. Also a contour map at the same scale was prepared. Both these maps were then converted to digital form using digitization and stored in ILWIS. Digitization which is the most time consuming part of the analysis, was carried in parts to minimise the digitization errors. Then the digitized map was corrected for any type of error such as proper joining of the streams, proper overlaying of the segments etc. The system then edits the coverage and splits the stream of the higher order automatically at the point where they meet. Individual stream (segment) lengths are computed by default and stored in the order table alongwith the order of each stream. The area and perimeter of the basin can be computed after converting segment (boundary) map to polygon map. After converting the

contour map into digital form, it was rasterised. Then interpolation from isolines was carried out on this map. This interpolated map gives the elevation at each point(pixel) in the basin.

5.2 EVALUATION OF GEOMORPHOLOGICAL CHARACTERISTICS

For stream order, Strahler's ordering system, has been followed. According to this ordering system, which is applied through ILWIS over the entire drainage network of the study area it is found that it is a seventh order basin. In the system, length of each stream is stored in a table. Then after adding length of each stream for a order we can get the total stream lengths of each order. The total stream length divided by the number of stream segment (N_u) of that order gives the mean stream length L_u for that order. The plot of logarithm of mean stream length (ordinate) as a function of order (abscissa) yields a set of points lying essentially along a straight line.

Horton's law of stream number states that the number of stream segments of each order is in inverse geometric sequence with order number i.e.

$$N_u = R_b^{u-k} \qquad \text{.......(1)}$$

Where k is the order of trunk segment, u is the stream order, N_u is the number of stream of order u and R_b is a constant called the bifurcation ratio. When logarthim of the number of streams is plotted against order it shows a linear relationship.

Horton inferred that mean drainage basin areas of progressively higher order should increase in a geometric sequence, as do stream lengths. The law of stream areas may written as :

$$A_u = A_1 R_a^{u-1} \qquad \text{......(2)}$$

where A_u is the mean area of basin of order u. The areas of fourth and higher order streams have been found by ILWIS. The areas of lower order basin was estimated using the relationship between area of any order and area of highest order as given below:

$$A_u = A_1 R_b^{u-1} (R_{lb}^{u}-1)/(R_{lb}-1) \qquad \text{........(3)}$$

Where A_1 is the mean area of first order basin R_b is the bifurcation ratio and R_{lb} is Horten's term for the length ratio to bifurcation ratio. In this relationship, only A_1 is unknown, so A_1 can be calculated. Now using the value of A_1 the other mean areas are computed.

Bifurcation, length and area ratios are calculated as the slope of the best fit lines through these plotted points given by the Horton's laws of stream numbers, lengths and areas respectively.

5.3 TIME AREA DIAGRAM

The time area methods were developed in recognition of the importance of the time distribution of rainfall on run-off in the hydrologic design of storage and regulation of works. The central idea in these methods is a time contour or an isochrone, The time area diagram, indicates the distribution of travel time of different parts of the watershed. In GIS environment the derivaton of TA diagram is significantly easier. Maidment (1993) used the GIS approach for derivation of TA diagram. In this study direction and velocity maps were generated in spatial form. A grid of flow direction was defined using a DEM of the watershed. In the present study due to non-availability of velocity components the above approach could not be adopted. The time area diagrams were prepared using the following approach:

- Measure the distance from the most upstream point in the basin to the outflow location along the principal water course.
- Preparation of time-area diagram is done by assuming that the time of travel between any two points is proportional to the distance and inversely proportional to the square root of the slope between them.

  $T = KL/\sqrt{S}$ ....(4)

  Where t is time of travel

  L is the length of the stream

  S is the slope of the stream

  K is propotionality constant

- An initial estimate of the time of concentration may be obtained using the Kirpich's formula.

  $t_c = 0.06628L^{0.77}H_{0.305}$ ....(5)

Where t is concentration time in hours

L is the length of stream in km

H is the average slope of the stream

Substituting the values of L and H in the above equation we get the value of time of concentration tc for each catchment

- This value of tc may be substituted in the above equation and then may be rearranged in the form:

$$K = tc\sqrt{S_A} / L \qquad \text{........(6)}$$

Substituting the known values of tc, L and SA in this equation the value of K may be computed.

- Knowing the value of constant of propotionality K the equation (5) may be used to calculate time of travel between the two points in the catchment. Starting from the basin outlet the time of travel of various points over the catchment is thus progressively calculated.
- All the values of the time of travels for each stream are then denoted on the map at the begining of the stream. Now these points were transferred in the digital form. Using interpolation technique a map of time distribution was then drawn through these points.
- From the time distribution map values a map at an interval of 60 minutes was prepared. The area for each time interval was measured and these values were tabulated.

5.4 COMPUTATION OF DESIGN STORM

Since the rainfall-runoff records for this catchment is not available, recourse is made to obtain the synthetic unit hydrograph based on the regionalised regression equations recommended by the Central Water Commission, India. The time base of this 1 hour unit hydrograph for the catchment is 24 hours. The duration of the design storm as per the recommended practice is taken as equal to this 24 hour for this catchment. The India Meteorological Dept. has published the PMP atlas for the whole country. The point PMP value as obtained from this atlas are given in the report prepared by CES for each catchment.

The 2-hour distribution of this rainfall is given in previous chapter for each catchment. First the duration of this rainfall was converted to 1-hour. The computed PMP rainfall excess increments are to be brought to a critical chronological pattern found in the observed storm characteristic of the basin under study in order to produce critical flow rates. For Jawai dam catchment critical time sequencing was done for four cases. First case is the sequencing in one bell mode. In this the peak rainfall is kept in the middle. In two bell case the peak value of first 12 hours is made like one bell case, in this way two bells for two blocks of 12 duration each was formed. In three bell case same procedure is adopted after dividing the entire duration in three equal parts. In the last case i.e. four bell case entire duration was divided in the equal interval of 6 hours each.

5.5 GIUH BASED CLARK MODEL

In this study, the peak characteristics of the IUH as obtained in Eqs. (1) & (2) given in chapter 1, are utilised for the evaluation of Clark model parameters. Once the parameters of this GIUH based Clark model are known, the complete IUH may be derived. The step-by-step explanation of the procedure for estimating the design flood using the proposed approach is given here under:

- Excess rainfall hyetograph is computed either by uniform loss rate procedure or by SCS curve number method (Soil Conservation Service, 1971) or by any other suitable method.
- As mentioned above, the direct determination of the velocity, V, in Eqs. (1) & (2) is not possible for ungauged catchments. And so, a relationship between the equilibrium velocity and the excess rainfall intensity is developed. It is assumed that the velocities corresponding to discharges passing through the gauging section at different depths of water flow are known from observations. The steps involved in this approach are given below.
  - (i) Let these velocities and discharges be the equilibrium velocities V and the corresponding equilibrium discharges Q_e.
  - (ii) For these Q_e find the corresponding intensities i of excess rainfall from the expression:

$$i = \frac{Q_e}{0.2778A} \qquad \ldots\ldots(6)$$

where A is the area of the catchment in sq. km.

(iii) From the pairs of such V and i, develop the relationship between the equilibrium velocity and the rainfall excess intensity in the form: $V = a\, i^b$ 0.

It is to be noted here that this approach though requires the information of discharges and velocities at the gauging site does not mean that it can be applied for the gauged catchments only. For the ungauged catchments too, this information may easily be obtained by gauging the stream intermittently for all ranges of depth of flow during one or two monsoon seasons. Also, it has been assumed here that the flow at the outlet is contributed from the whole catchment at the time of peak flow. This is a condition which would invariably be satisfied for the design floods for any catchment.

- compute the time of concentration, T_c (in hours) using the equation:

$$T_c = 0.2778 \frac{L}{V} \qquad \ldots\ldots(7)$$

where L is the length of the main channel in kms..

V is the estimated velocity m/sec..

- Taking the time of concentration as computed in step(c), obtain the time-area diagram for the catchment at an hourly time interval with the help of non-dimensionalised plot between percent cumulative isochronal area and the percent time of travel.
- Compute the peak discharge (q_{pg}) of GIUH given by Eq.(1).
- Using Newton-Raphson's iterative procedure compute the value of the storage coefficient R such that the peak of the IUH by Clark model is equal to q_{pg} (within tolerable limits) obtained in step(e).

- Compute the instantaneous unit hydrograph (IUH) using the GIUH based Clark Model with the help of final values of storage coefficient (R) obtained in step (f) above, time of concentration (T_c) and the time-area diagram.
- Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour.
- Convolute the design storm rainfall excess hyetograph with the unit hydrograph obtained in step (h) to obtain the standard project flood hydrograph.

5.6 COMPUTATION OF DESIGN FLOOD

The design storms computed using the method discussed under section 5.1 are used as input to the GIUH model to compute the design flood hydrograph. The geomorphological parameters such as length of the main stream, bifurcation ratio, length ratio and area ratio alongwith the time area diagram are supplied to the model. Flood hydrograph corresponding to the supplied design storm are computed using the principle of superposition and principle of proportionality of the unit hydrograph. The computation for design flood direct surface runoff is performed using the convolution equation which is given as

$$Q_i = \sum_{j=1}^{i} X_j U_{i-j+1} = \sum_{j=1}^{i} U_j X_{i-j+1} \qquad \text{.........(8)}$$

Where

X is the rainfall excess and U is the unit hydrograph ordinate.

i is the number of pulses of input

The excess rainfall is computed using the design loss rate over the design storm hydrograph. The computation of direct surface runoff using the equitation No. is added with design base flow to compute the design flood hydrograph ordinate.

6 .0 ANALYSIS AND DISCUSSION OF RESULTS

The methodology discussed in chapter five have been utilized to analyse the data of four dam catchments of Rajasthan. In this chapter the analysis procedure followed for each catchment and the results obtained are discussed. These are explained as follows:

6.1 ANALYSIS FOR JAWAI DAM CATCHMENT

Different parameters for Jawai dam catchment has been prepared using the capability of ILWIS GIS package. Fig. 6.1 illustrates the drainage network map of Jawai dam catchment. From this figure it is obtained that the catchment is of the 7^{th}. Order. Digital Elevation Model (DEM) of this catchment has been developed and shown in Fig. 6.2. For the catchment the elevation varies from 300 to 1100 m.

The various geomorphological characteristics of Jawai dam catchment required for the running the GIUH model and evaluated using the ILWIS software. Table 6.1 given below provides the details of these geomorphological characteristics for the Jawai dam catchment. From this table it is observed that the bifurcation ration, length ratio and area ratio, which are non-dimensional characteristics are 3.65, 1.88 and 4.032 respectively for the Jawai dam catchment. These values are within the limits which have been reported in the literature.

Table 6.1 Geomorphological characteristics of Jawai dam catchment

Order	No. of streams	Average Length	Average area	Value of constants
1	2221	0.561	0.1476	R_b=3.65 R_l=1.88 R_a=4.032
2	523	0.751	0.8162	
3	124	1.790	3.50	
4	34	3.880	13.76	
5	8	4.850	52.05	
6	3	20.069	190.01	
7	1	16.82	712.66	

The time area diagram is one of the important inputs for running the GIUH based Clark model. It provides the shape of IUH without considering the storage effects of the

catchment. The DEM data generated from ILWIS for Jawai dam catchment are utilized to develop isochronal ma for the catchment in which the isochrone are plotted at hourly interval. A time area diagram for Jawai dam catchment has been prepared taking the contributing area on Y- axis and time of travel on X-axis. For preparing the time area diagram also the capability of ILWIS ackage is utilized. The time area diagram for Jawai dam catchment is shown in 6.3. In order to provide the flexibility in the interpolation of time area diagram a non-dimensional time area has been prepared taking t/tc on X-axis and a/ac (ratio of total contributing area and the catchment area) on Y-axis (Fig. 6.4). The ordinate of the non-dimensional curves is used as input for the time area diagram. The data for design storm has been prepared using the methodology discussed in the chapter 5 under section 5.4. The values for four cases are given in table 6.2.

Each set of design storm data together with geomorphological characteristics, time area diagram and in initial paramter values are supplied to the GIUH based model and the model has been run. The design flood hydrograh computed for the Jawai dam catchment are shown in Fig. 6.5 to 6.8 considering the design storm of one, two, three and four bell respectively. The values for one case i.e. one bell case is also given in table 6.3. In these figures the case 2 represent the flood hydrograph obtained from convoluting the excess rainfall hyteograph with the UH developed in the report of CES Pvt. Ltd. However case 1 refers to the design flood hydrograph resulting due to application of GIUH based Clark model for the computation of design flood hydrograph. From these figures it is observed that the design flood hydrograph obtained for case 1 is higher than that of case 2. However the difference on design flood hydrograph peak corresponding to design storm of two bell system is maximum for the two cases and minimum for the design storm of one bell system of design storm. The velocity is one of the important parameter in the GIUH model. Methodology has been prepared elsewhere (Chowdhry et. al.) for the computation of the velocity using the limited stage discharge observations and hydraulic characteristics of main river channel. Unfortunately for this site no historical records were available and also the information regarding the hydraulic characteristics were inadequate for evaluating the velocity. Under the circumstances reasonable values of velocity of 3.88 m/s is utilised for each PMP.

Table 6.2 Design storm values for four cases for Jawai dam catchment

Hour	One bell	Two bell	Three bell	Four bell
0	0	0.0	0.0	0.0
1	0.96	0.96	1.44	1.44
2	0.96	1.44	1.44	2.88
3	0.96	1.44	2.40	2.88
4	1.44	1.44	2.88	3.36
5	1.44	2.4	2.88	3.84
6	1.44	2.88	3.36	8.16
7	1.44	3.84	3.84	0.96
8	1.92	8.16	8.16	1.92
9	2.40	3.36	0.96	2.40
10	2.88	2.88	1.44	2.40
11	3.84	2.4	1.44	1.44
12	8.14	1.92	1.92	1.44
13	3.36	1.44	2.40	1.44
14	2.88	1.44	1.44	1.44
15	2.40	1.44	1.44	1.44
16	1.44	1.44	1.44	1.44
17	1.44	1.44	1.44	1.44
18	1.44	1.44	1.44	1.44
19	1.44	1.44	1.44	1.44
20	1.44	0.96	0.96	0.96
21	1.44	0.96	0.96	0.96
22	0.96	0.96	0.96	0.96
23	0.96	0.96	0.96	0.96
24	0.96	0.96	0.96	0.96

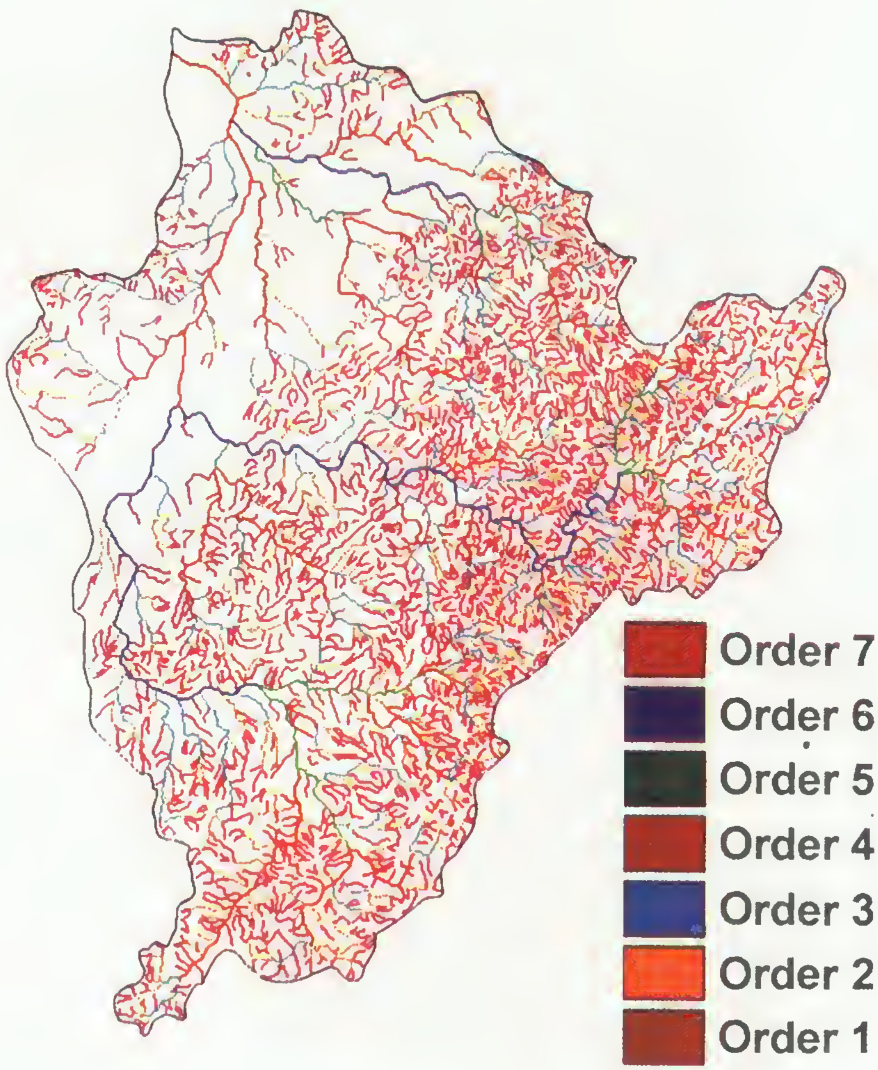


Fig.6-1 Drainage Network Map of Jawai Dam Catchment

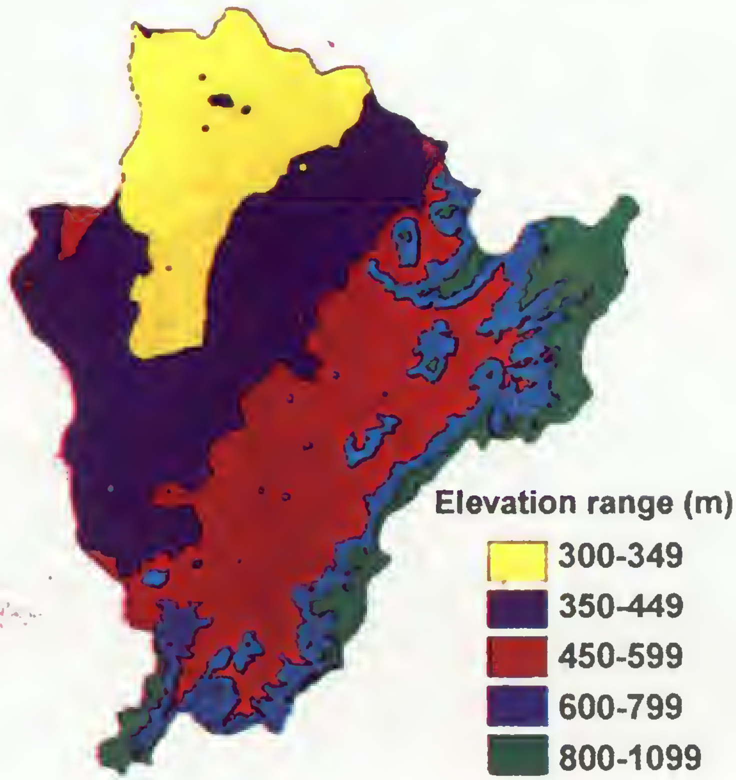


Fig.62 Digital Elevation Map Of Jawai Dam Catchment

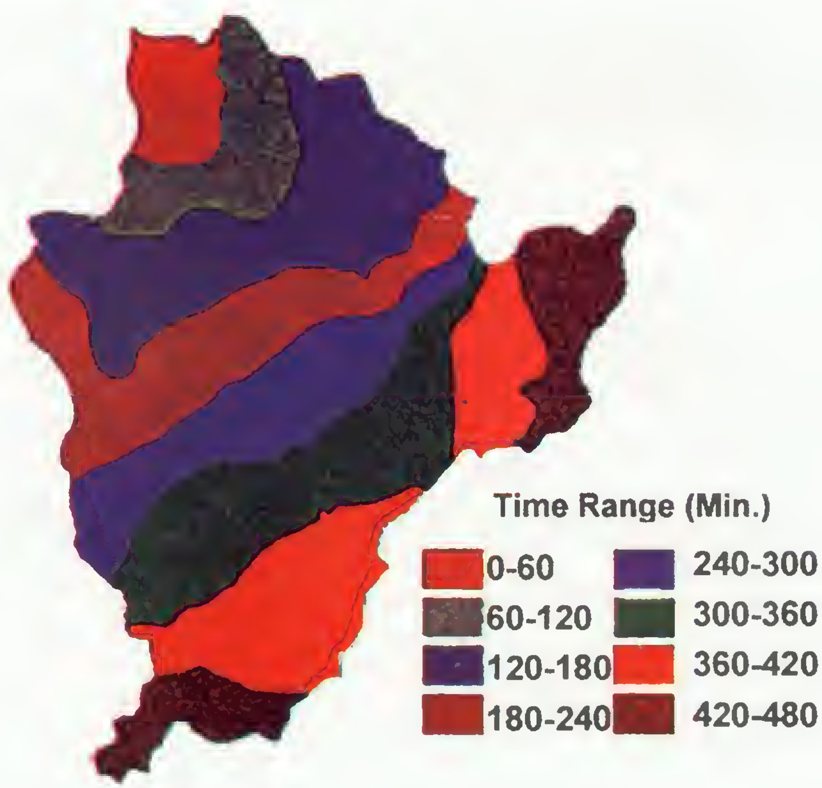
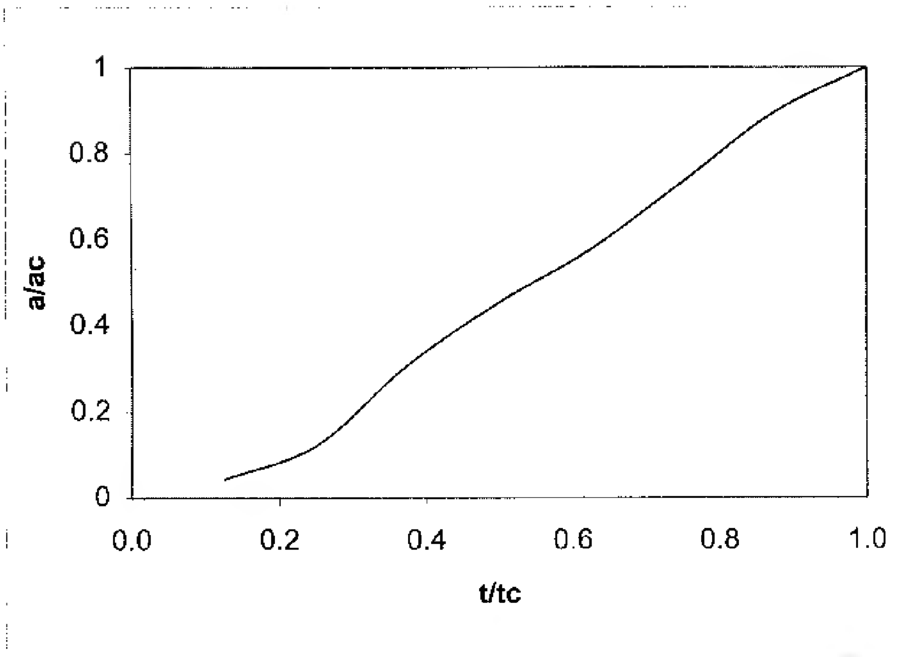


Fig.63 Time Area Map of Jawai Dam Catchment



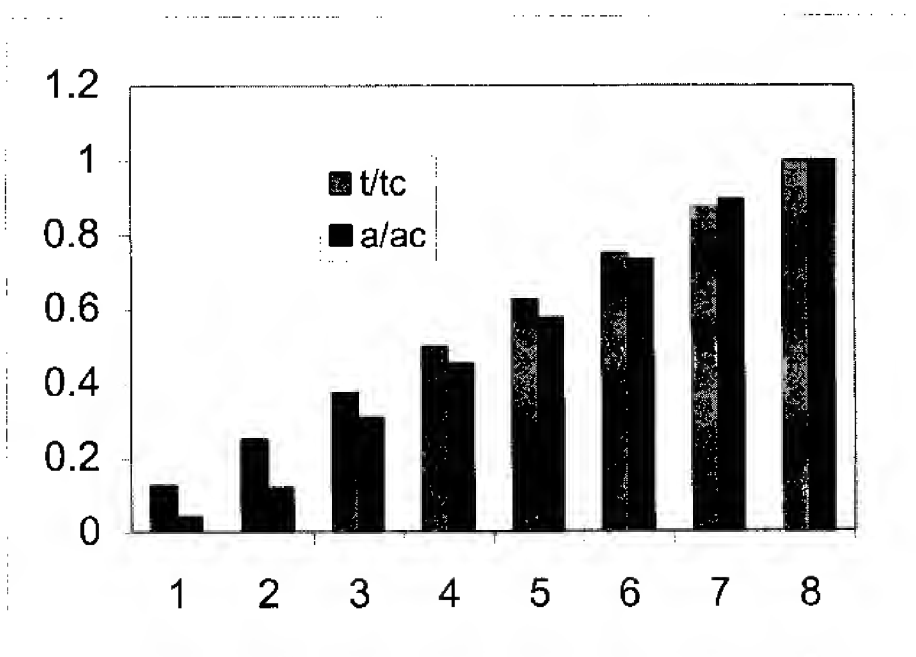


Fig.6.4 Time Area Diagram of Jawai Dam Catchment

Fig5.5 Rainfall-runoff simulation(One Bell)Jawai Dam Catchment

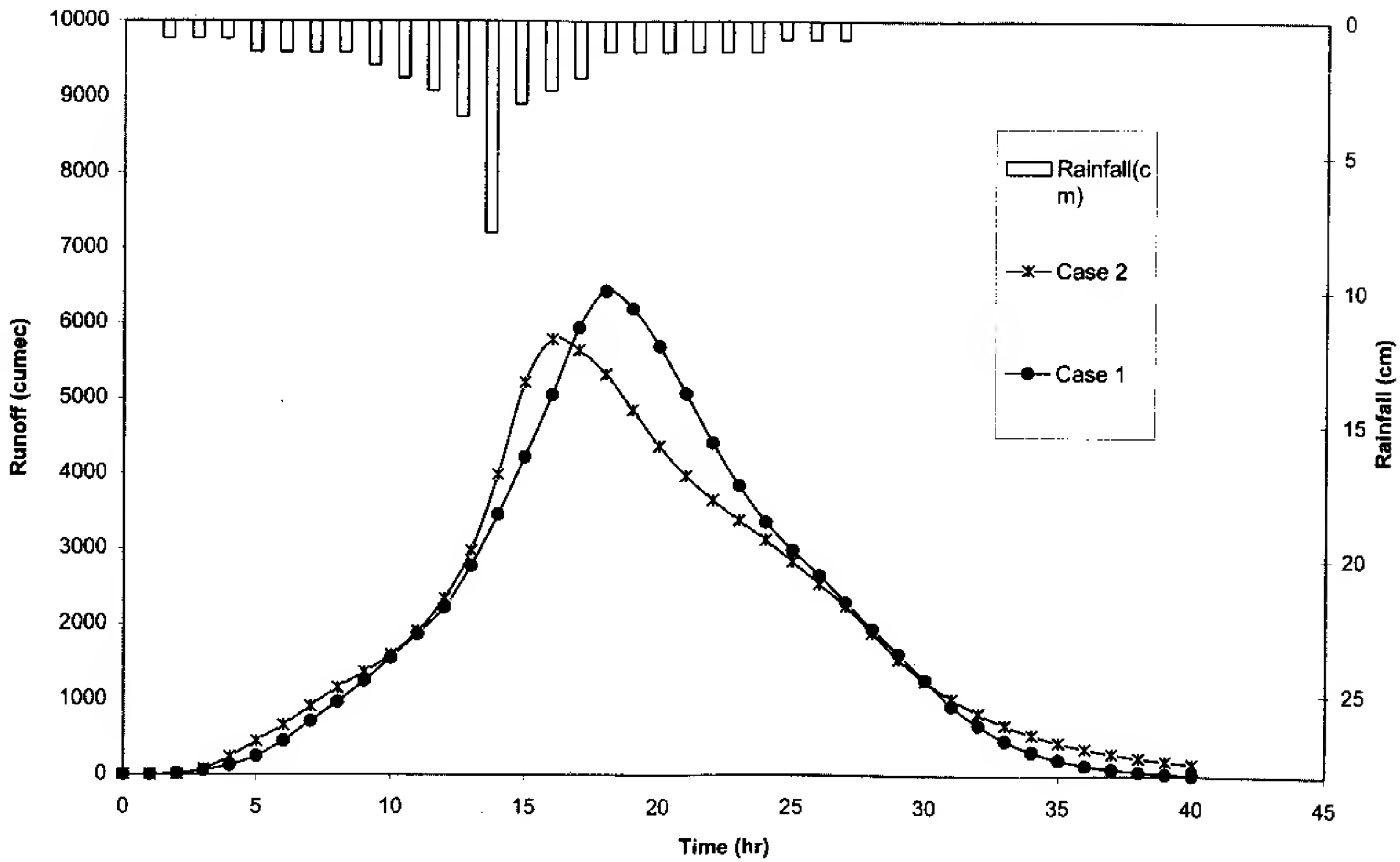


Fig.6 Rainfall-runoff simulation (Two Bell) Jawai Dam Catchment

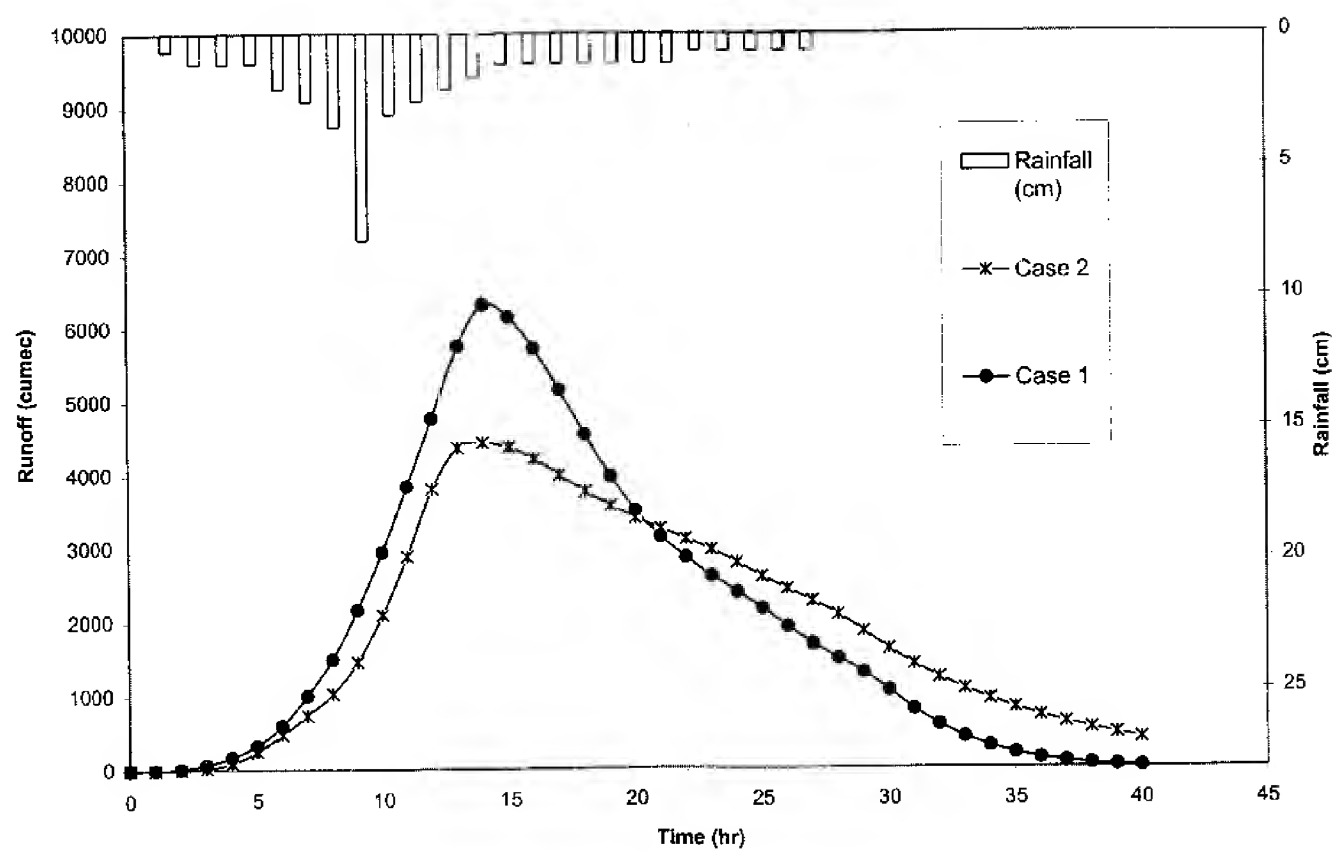


Fig.6: Rainfall-runoff simulation (Three Bell) Jawai Dam Catchment

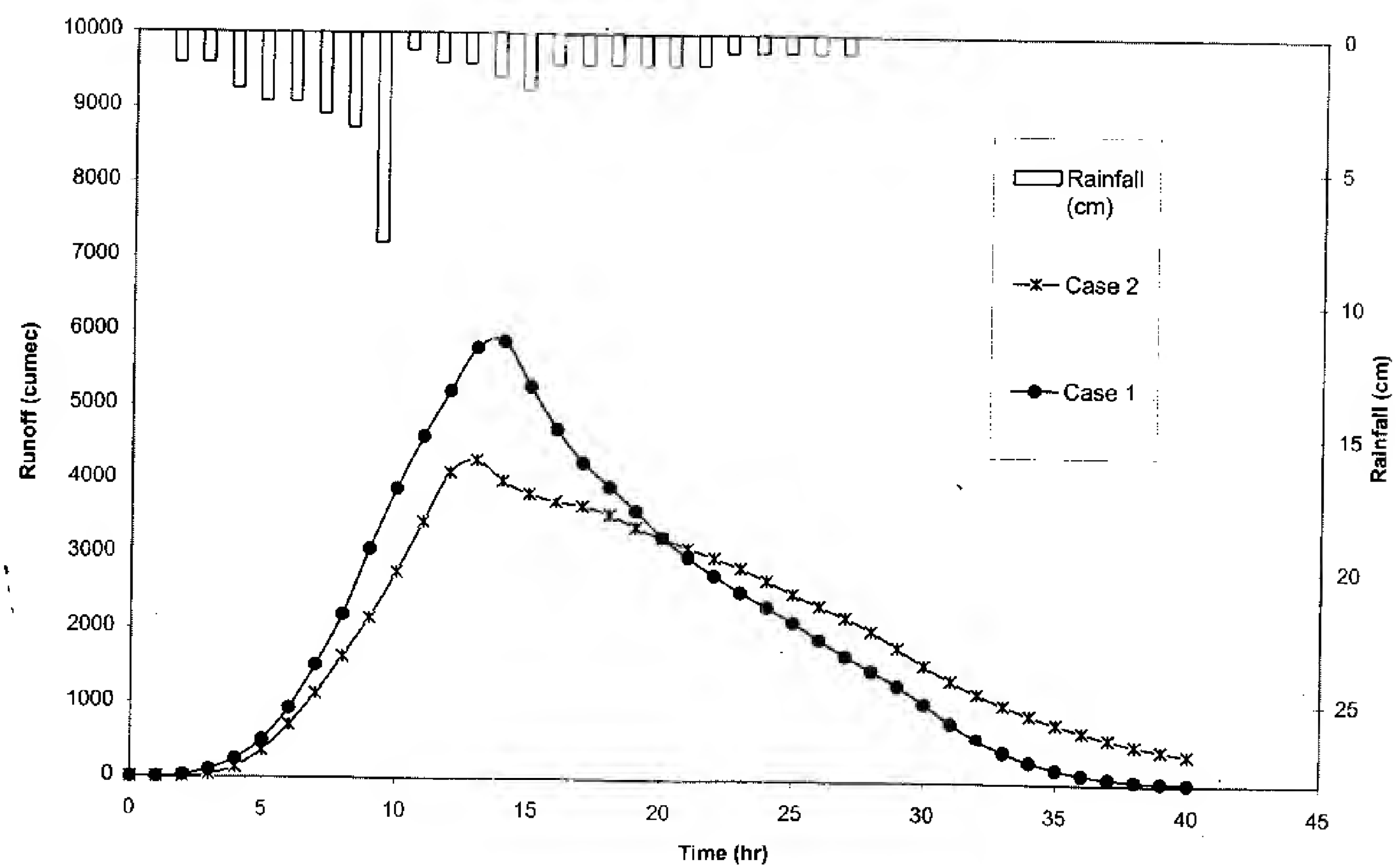


Fig.5.8 Rainfall-runoff simulation (Four Bell) Jawai Dam Catchment

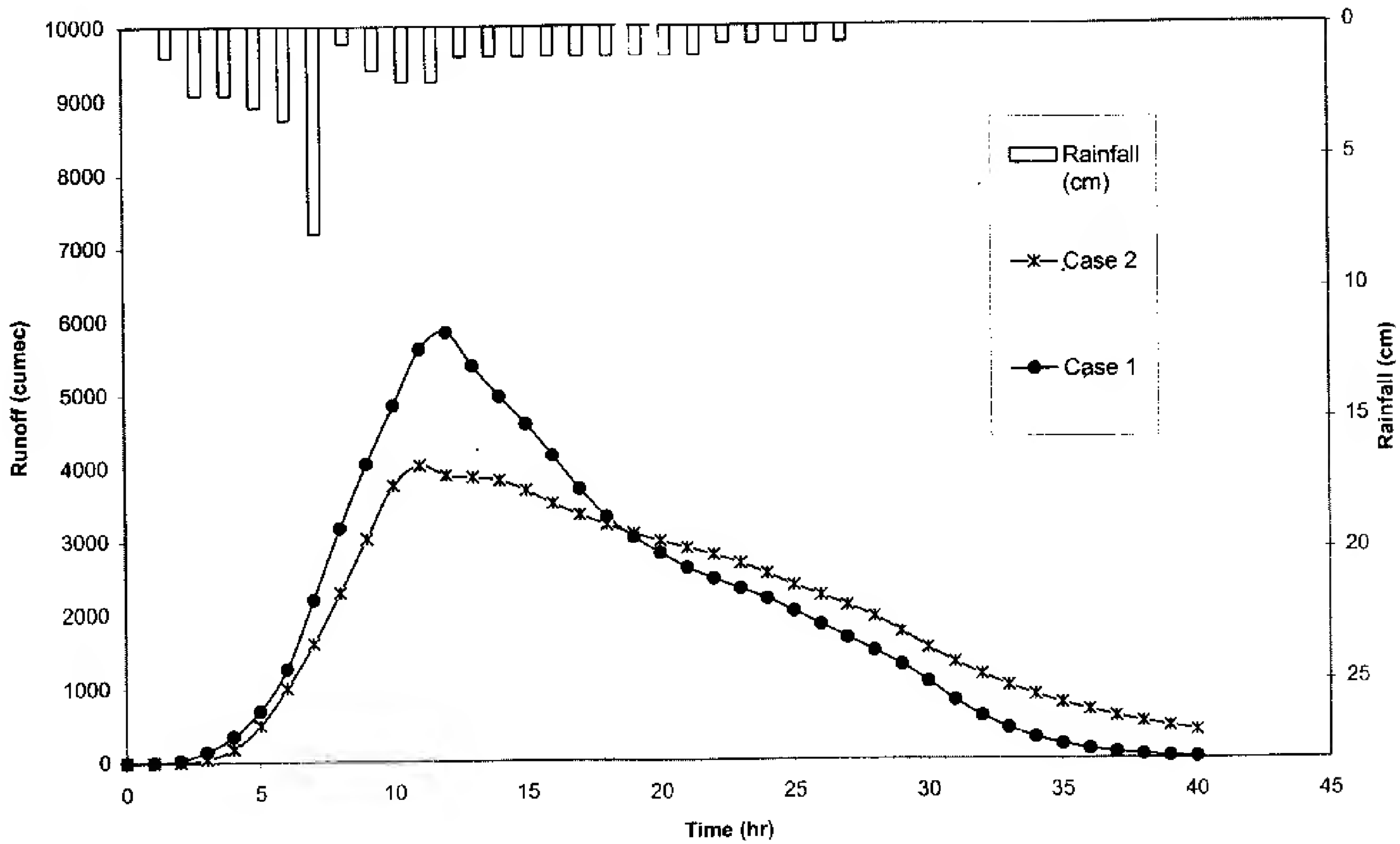


Table 6.3 Design flood values for case 1 and case 2 for Jawai dam catchment

Hours	Case 2	Case 1	Hour	Case 2	Case 1
1	0	0	21	2464.988	2397.978
2	134.264	215.6	22	2297.198	2290.554
3	816.389	560.95	23	2112.827	2177.802
4	2244.482	1068.6	24	1962.762	2022.282
5	3341.468	1787.5	25	1848.839	1868.73
6	3766.518	3011.5	26	1777.179	1726.932
7	4120.185	4186.25	27	1702.628	1594.53
8	4334.084	4683.05	28	1499.348	1465.182
9	4267.674	4926.55	29	1220.361	1344.558
10	4070.213	5010.95	30	993.286	1160.256
11	3909.492	4865.55	31	808.463	895.632
12	3754.017	4513.3	32	658.031	666.132
13	3538.592	4158.75	33	535.59	481.332
14	3260.429	3846.00	34	435.931	339.123
15	3105.974	3565.301	35	354.817	232.182
16	2995.695	3213.95	36	288.795	153.132
17	2858.133	2961.95	37	235.058	101.658
18	2746.167	2812.2	38	188.679	65.958
19	2655.034	2657.342	39	152.702	38.508
20	2572.693	2510.454	40	123.257	21.708

6.2 ANALYSIS FOR GAMBHIRI DAM CATCHMENT

The drainage netwrok map of Gambhiri dam catchment is presented in fig. 6.2. From this figure it is revealed that the catchment is of the 6^{th}. Order. Digital Elevation Model (DEM) of this catchment has been developed and shown in Fig. 6.10. For the catchment the elevation varies from 300 to 1100 m. Table 6.3 provides the details of these

geomorphological characteristics for the Gambhiri dam catchment. From this table it is observed that the bifurcation ration, length ratio and area ratio, which are non-dimensional characteristics are 4.00, 1.946 and 4.49 respectively for the Gambhiri dam catchment. These values are within the limits which have been reported in the literature.

Table 6.4. Geomorphological characteristics of Gambhiri dam catchment

Order	No. of streams	Average Length	Average area	Value of constants
1	1062	0.794	0.492	R_b=4.00 R_l=1.946 R_a=4.49
2	247	1.187	2.928	
3	68	2.781	13.578	
4	16	7.662	57.944	
5	4	17.995	238.839	
6	1	13.430	969.27	

The DEM data generated from ILWIS for Gambhiri dam catchment are utilized to develop isochronal map for the catchment in which the isochrone are plotted at hourly interval. A time area diagram for Gambhiri dam catchment has been prepared taking the contributing area on Y- axis and time of travel on X-axis. For preparing the time area diagram also the capability of ILWIS package is utilized. The time area diagram for Gambhiri dam catchment is shown in 6.11. In order to provide the flexibility in the interpolation of time area diagram a non-dimensional time area has been prepared taking t/tc on X-axis and a/ac (ratio of total contributing area and the catchment area) on Y-axis(Fig. 6.12). The ordinate of the non-dimensional curves is used as input for the time area diagram. The values for design storm as computed in last chapter four cases are given in table 6.5 given below:

Table 6.5 Design storm values for four cases for Gambhiri dam catchment

Hour	One bell	Two bell	Three bell	Four bell
0	0.0	0.0	0.0	0.0
1	0.45	0.06	0.86	0.86
2	0.69	0.86	1.02	1.73
3	0.96	1.02	1.73	1.91
4	1.03	1.77	1.81	4.45
5	1.07	2.10	2.66	4.62
6	1.26	2.66	4.45	9.80
7	1.65	4.62	4.62	0.09
8	1.77	9.80	9.8	1.77
9	1.91	4.45	0.09	2.62
10	2.02	2.62	1.26	2.66
111	2.66	1.91	1.65	1.91
12	4.62	1.73	1.91	1.02
13	9.8	1.09	2.62	0.59
14	4.45	1.26	1.77	1.26
15	2.62	1.65	1.35	1.65
16	1.91	2.02	0.96	2.02
17	1.73	1.45	2.02	1.35
18	1.35	1.07	1.09	0.96
19	1.09	1.04	1.07	1.09
20	1.04	1.03	1.04	1.07
21	1.02	0.96	1.03	1.04
22	0.84	0.59	0.59	1.03
23	0.47	0.47	0.47	0.47
24	0.09	0.45	0.45	0.45

Each set of design storm data together with geomorphological characteristics, time area diagram and in initial parameter values are supplied to the GIUH based model and the model has been run. The design flood hydrograh computed for the Gambhiri dam catchment are shown in Fig. 6.13 to 6.16 considering the design storm of one, two, three and four bell respectively. The values for one case i.e one bell case is also given in table 6.6.

Table 6.6 Design flood values for case 1 and case 2 for Gambhiri dam catchment

Hours	Case 2	Case 1	Hour	Case 2	Case 1
1	0	0	21	7988.871	10772.1
2	1.951	15	22	7448.311	9548.301
3	45.85	74.05	23	6915.453	8456.65
4	184.416	196.95	24	6421.436	7403.05
5	446.236	418.2	25	5949.076	6442.55
6	792.112	770.75	26	5445.824	5611.05
7	1160.776	1240.2	27	4875.996	4838.15
8	1528.208	1780.45	28	4259.98	4075
9	1898.082	2330.8	29	3659.124	3303.8
10	2298.59	2861.85	30	3125.404	2539.55
11	2731.79	3389.6	31	2669.532	1852.15
12	3171.18	3934.65	32	2280.155	1313.35
13	3629.18	4549.8	33	1947.571	908.5
14	4247.299	5381.9	34	1663.499	632
15	5389.42	6510.7	35	1420.861	435.35
16	7091.655	7823.75	36	1213.614	296.9
17	8516.303	9350.5	37	1036.596	198.25
18	9143.736	10921.95	38	885.399	127.7
19	8945.802	11870.6	39	756.254	77.4
20	8503.532	11757	40	645.947	42.1

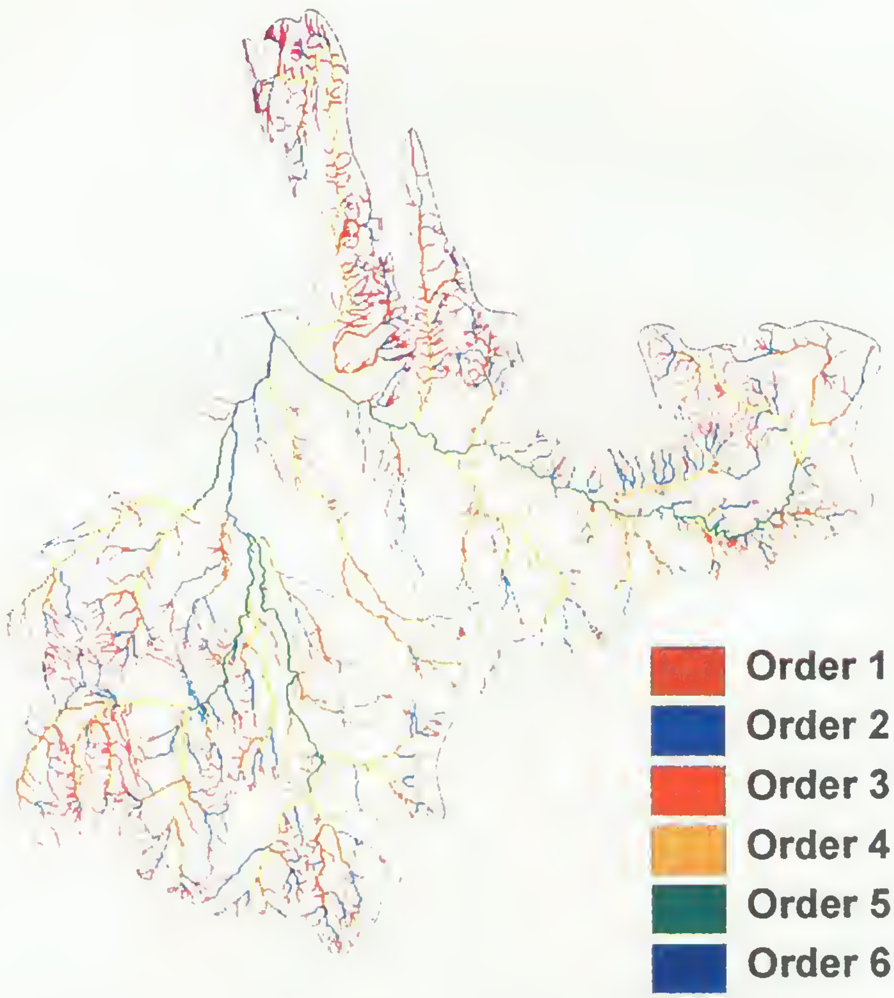


Fig.6.9 Drainage Network Map of Gambhiri Dam Catchment

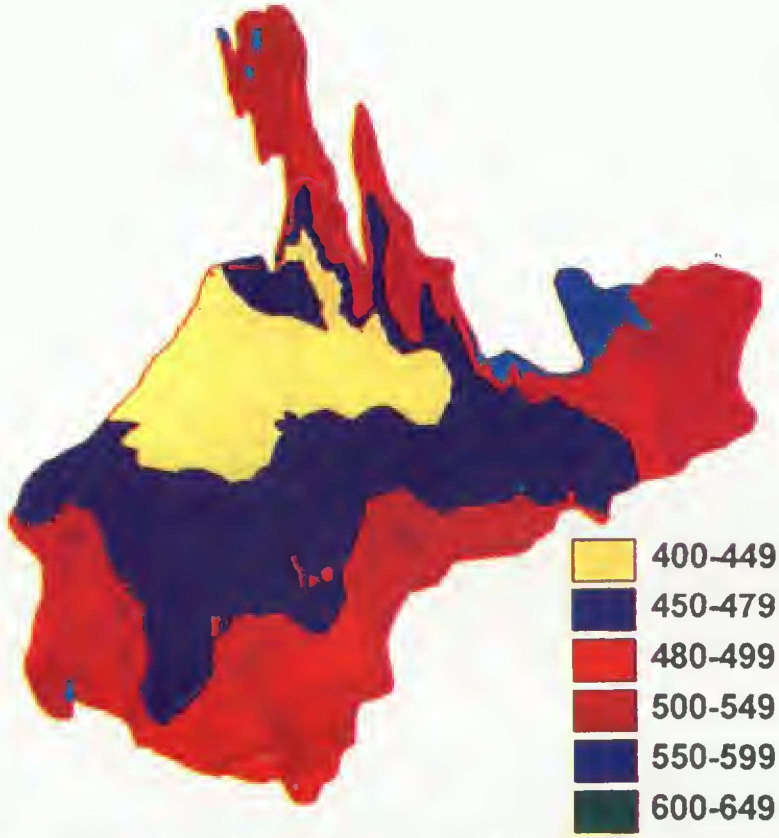


Fig.6·10 Digital Elevation Map of Gambhiri Dam Catchment

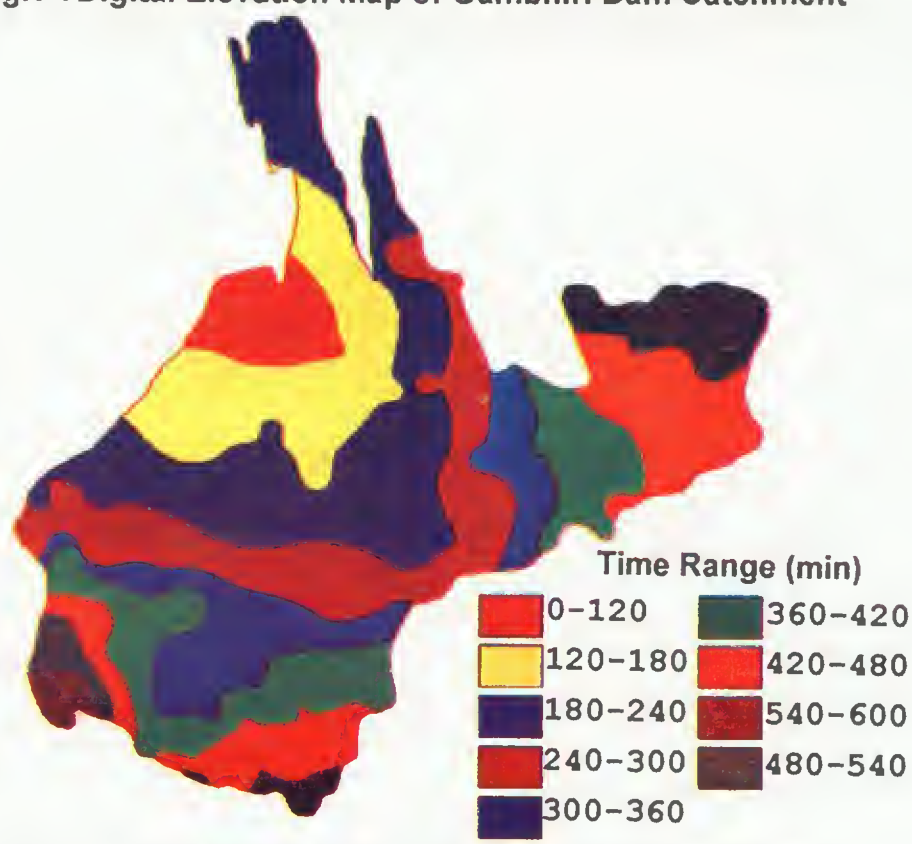


Fig.6·11 Time Area Diagram of Gambhiri Dam Catchment

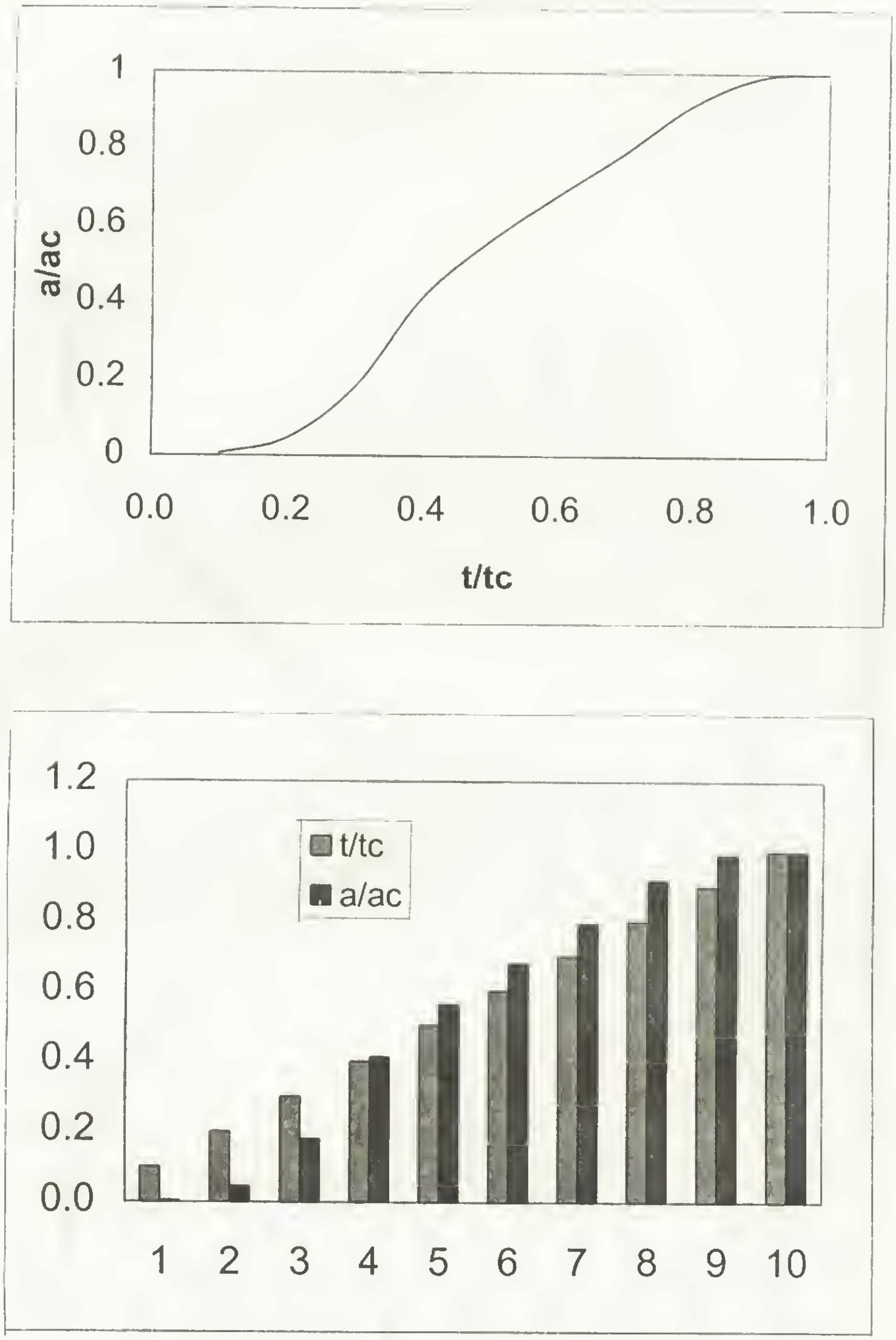


Fig. 6·12 Time Area Diagram of Gambhiri Dam Catchment

Fig. 6.13 Rainfall-runoff simulation (One Bell) Gambhiri Dam Catchment

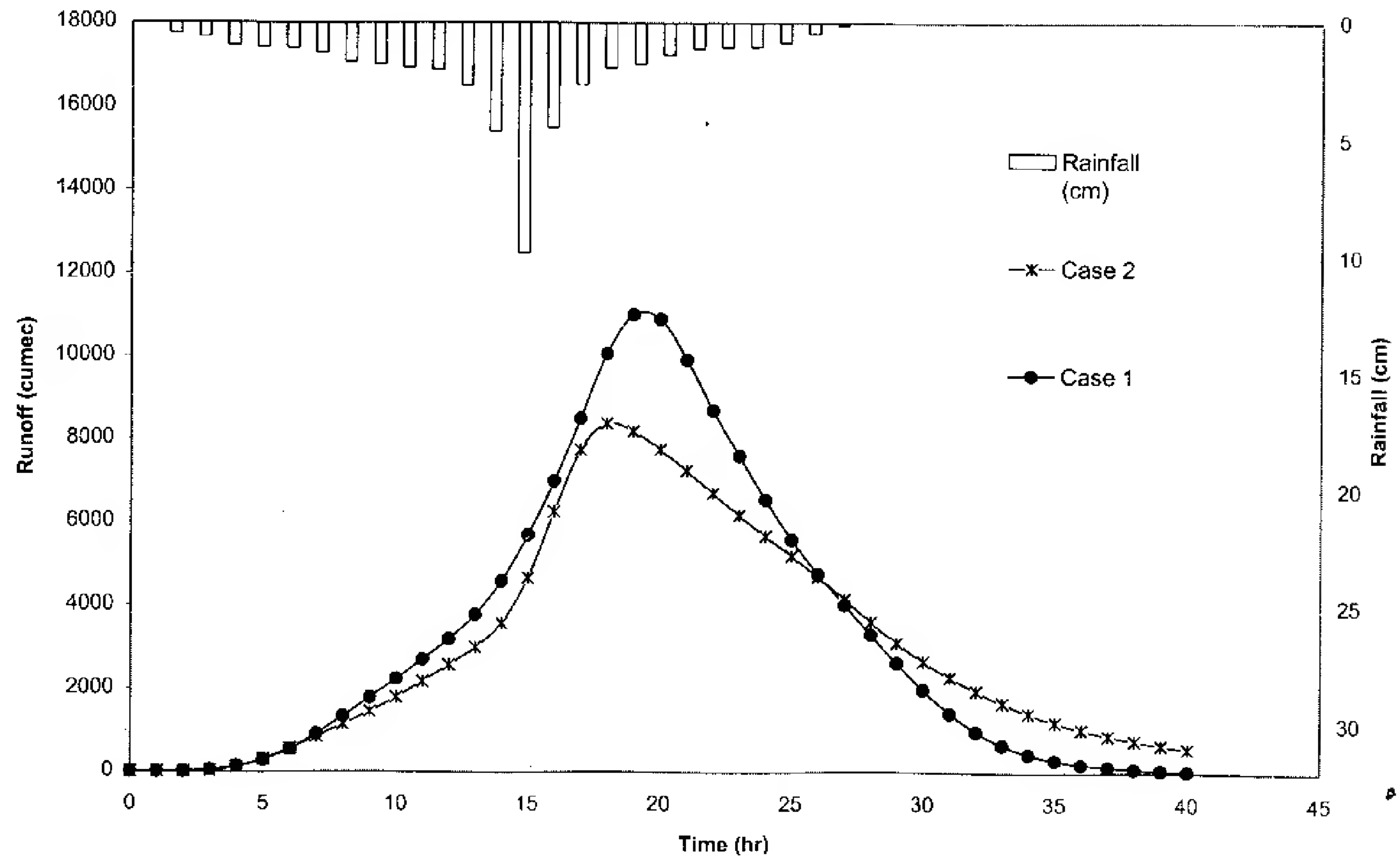


Fig. 6.14 **Rainfall-runoff simulation (Two Bell) Gambhiri Dam Catchment**

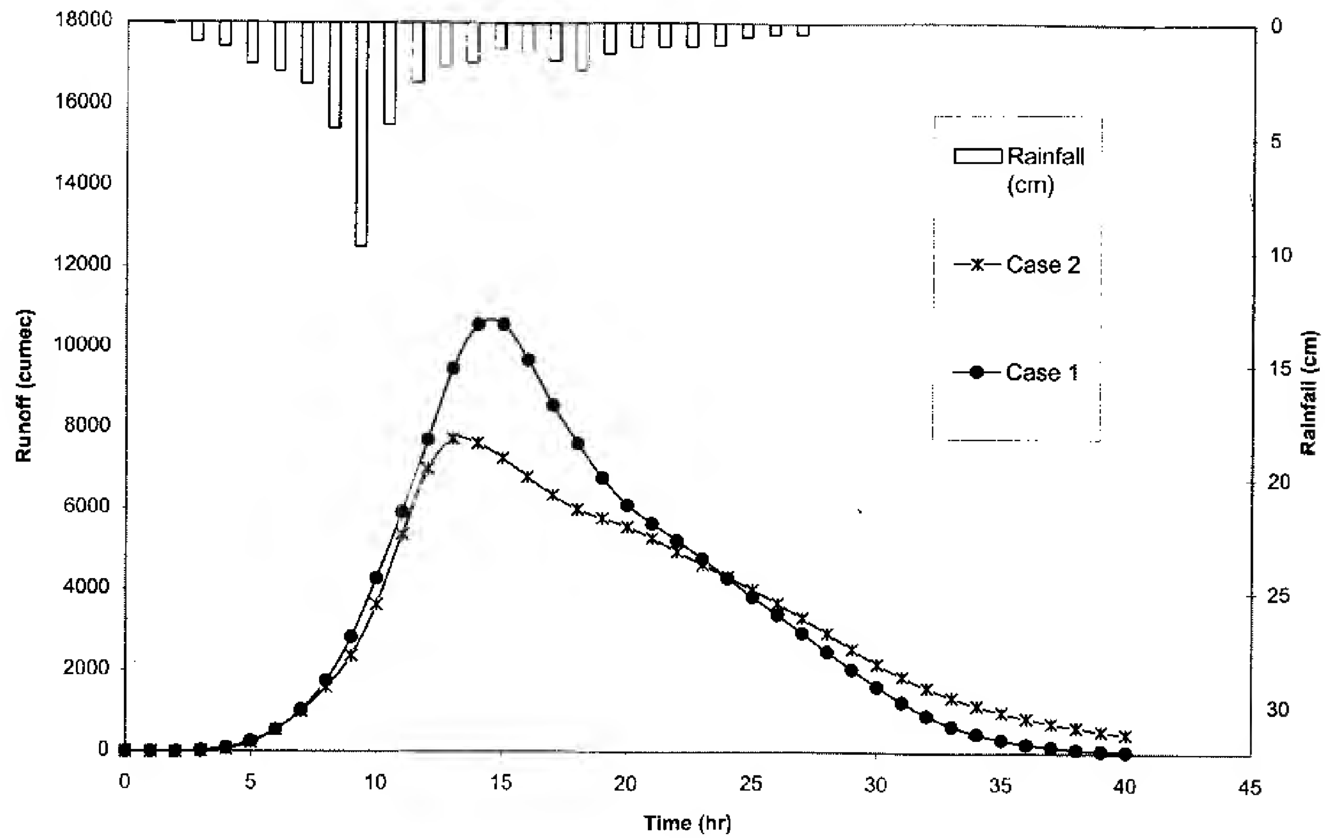


Fig. 6.15 **Rainfall-runoff simulation (Three Bell) Gambhiri Dam Catchment**

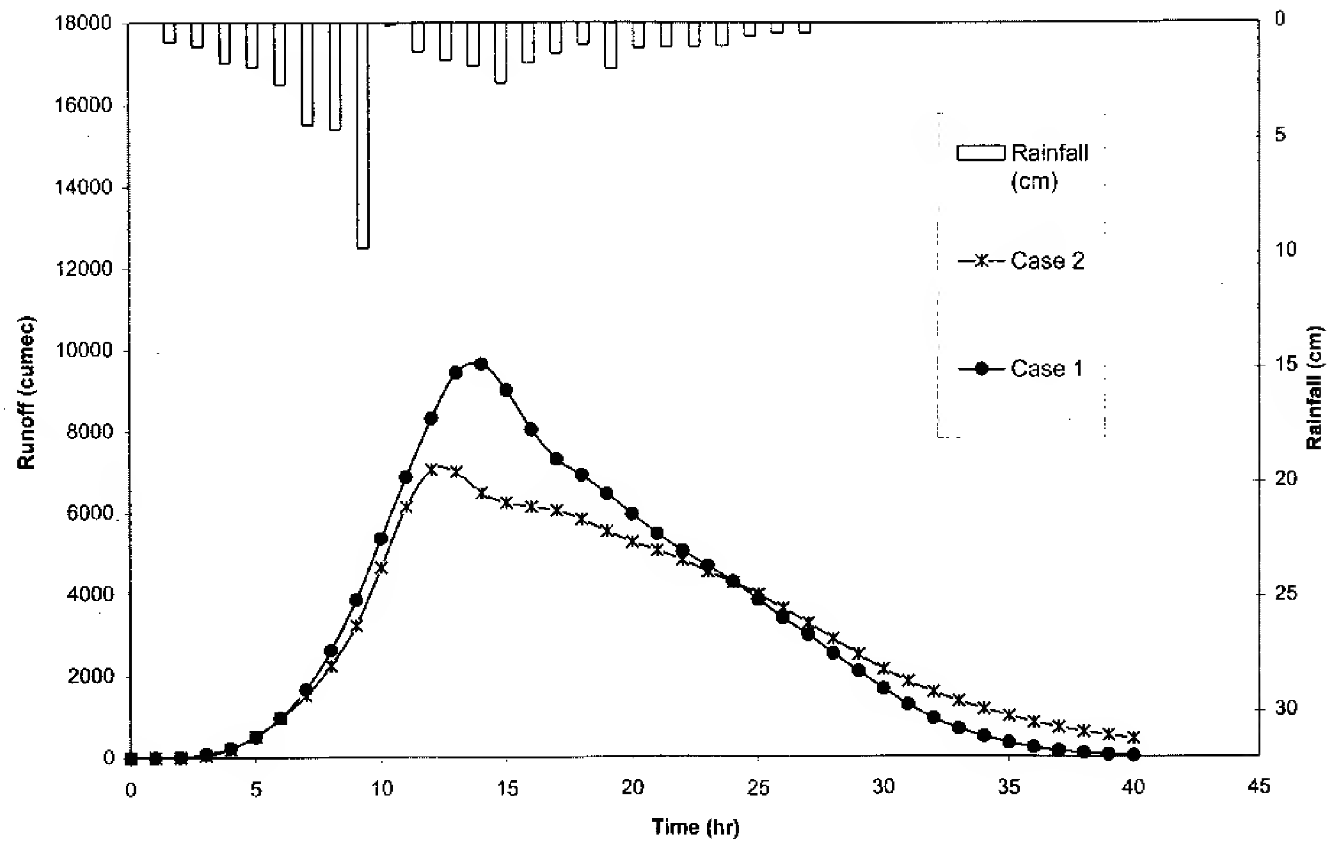
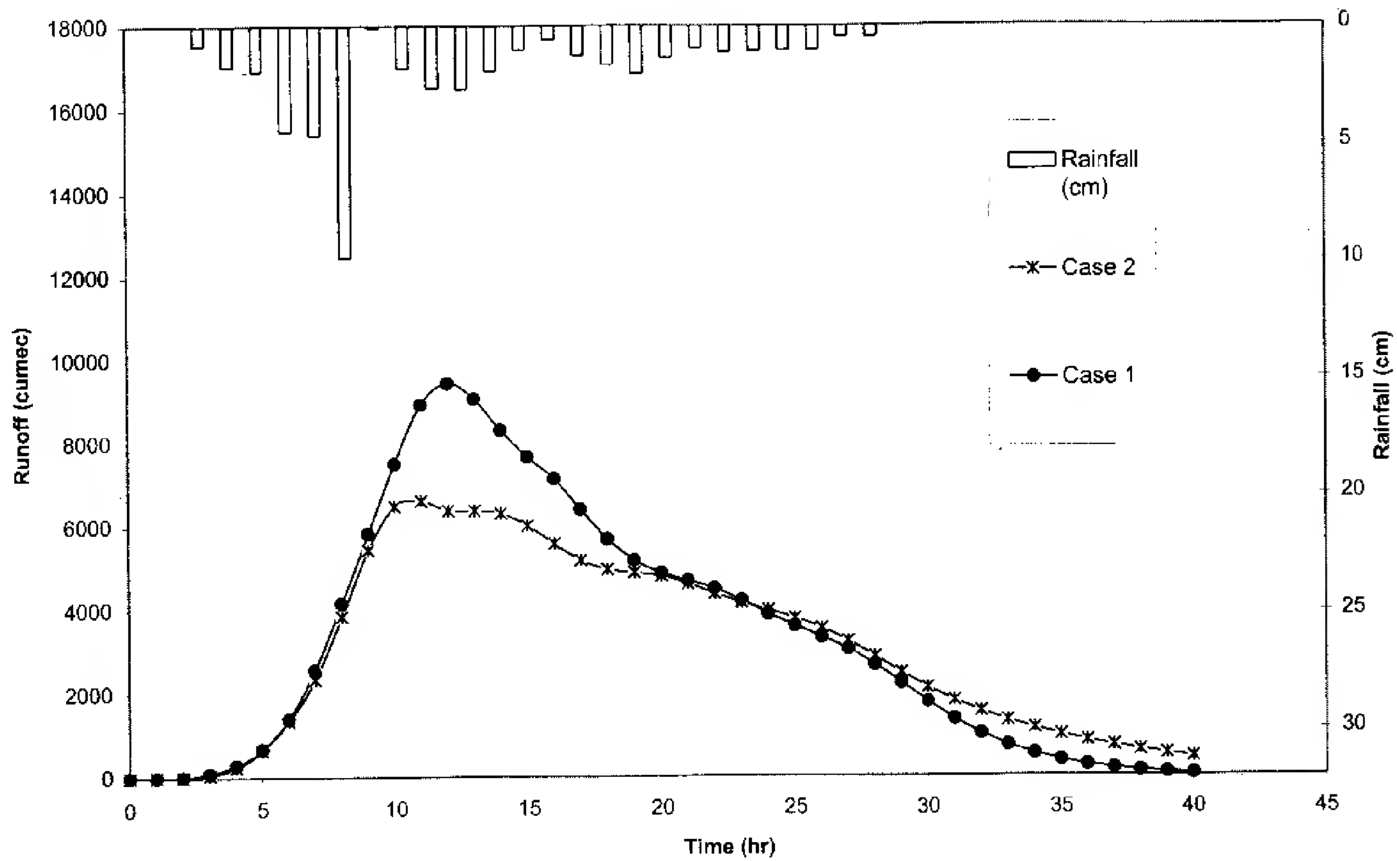


Fig. 6.16 **Rainfall-runoff simulation (Four Bell) Gambhiri Dam Catchment**



From these figures it is observed that the design flood hydrograph obtained for case 1 is higher than that of case 2. However the difference on design flood hydrograph peak corresponding to design storm of two bell system is maximum for the two cases and minimum for the design storm of one bell system of design storm. Unfortunately for this site no historical records were available and also the information regarding the hydraulic characteristics were inadequate for evaluating the velocity. Under the circumstances reasonable values of velocity of 4.25 m/s is utilised for each PMP.

6.3 ANALYSIS FOR SEI DAM CATCHMENT

The drainage network map of Sei dam catchment is illustrated in Fig.6.17. From this figure it is obtained that the catchment is of the 7th. Order. Digital Elevation Model (DEM) of this catchment has been developed and shown in Fig. 6.18. For the catchment the elevation varies from 300 to 1100 m. Table 6.7 provides the details of these geomorphological characteristics for the Sei dam catchment. From this table it is observed that the bifurcation ration, length ratio and area ratio, which are non-dimensional characteristics are 3.37, 1.71 and 3.71 respectively for the Sei dam catchment. These values are within the limits which have been reported in the literature.

Table 6.7. Geomorphological characteristics of Sei dam catchment

Order	No. of streams	Average Length	Average area	Value of constants
1	1315	0.522	0.111	
2	306	0.821	0.563	R_b=3.37
3	69	1.600	2.219	R_l=1.71
4	17	3.170	8.033	R_a=3.71
5	6	6.110	28.010	
6	2	9.150	96.020	
7	1	10.510	326.59	

The DEM data generated from ILWIS for Sei dam catchment are utilized to develop isochronal map for the catchment in which the isochrone are plotted at hourly interval. A time area diagram for Sei dam catchment has been prepared taking the contributing area on

Y- axis and time of travel on X-axis. For preparing the time area diagram also the capability of ILWIS package is utilized. The time area diagram for Sei dam catchment is shown in 6.19. In order to provide the flexibility in the interpolation of time area diagram a non-dimensional time area has been prepared taking t/tc on X-axis and a/ac (ratio of total contributing area and the catchment area) on Y-axis and shown in Fig. 6.20. The ordinate of the non-dimensional curves is used as input for the time area diagram. The data for design storm has been prepared using the methodology discussed in the chapter 5 under section 5.4. and the values are given in table 6.8.

Table 6.8 Design storm values for Sei dam catchment

Hour	Sei catchment
0	0.0
1	0.02
2	0.03
3	1.44
4	1.44
5	1.44
6	2.39
7	2.86
8	6.66
9	13.26
10	5.22
11	2.86
12	1.44
13	1.44
14	0.49
15	0.02

The model was run using each design storm data together with geomorphological characteristics, time area diagram and in initial parameter values. The design flood hydrograh computed for the Sei dam catchment are shown in Fig. 6.21 considering the design storm of

one bell and these values are also tabulated in table 6.9. From this figure it is observed that the design flood hydrograph obtained for case 1 is higher than that of case 2. Unfortunately for this site no historical records were available and also the information regarding the hydraulic characteristics were inadequate for evaluating the velocity. Under the circumstances reasonable values of velocity of 4.0 to 5.0 m/s is utilised for this PMP.

Table 6.9 Design flood values for case 1 and case 2 for Sei dam catchment

Hours	Case 2	Case 1	Hour	Case 2	Case 1
1	0	0	16	2243.282	2715.37
2	1.004	0.72	17	1619.528	2057.96
3	4.883	3	18	1139.461	1493.6
4	81.398	58.16	19	800.525	1068.82
5	324.31	198.8	20	562.406	755.57
6	612.503	445.78	21	395.116	510.36
7	862.66	734.14	22	277.588	316.09
8	1188.898	1033.36	23	195.013	182.48
9	1725.728	1491.92	24	136.999	88.42
10	2939.258	2402.77	25	95.893	43.8
11	4611.562	3637.74	26	67.014	19.2
12	5185.957	4785.64	27	46.725	7.5
13	4532.793	4967.48	28	32.237	1.59
14	3687.529	4346.63	29	21.943	0.06
15	2927.628	3497.14			

Fig.6.17 Drainage Network Map of Sei Dam Catchment

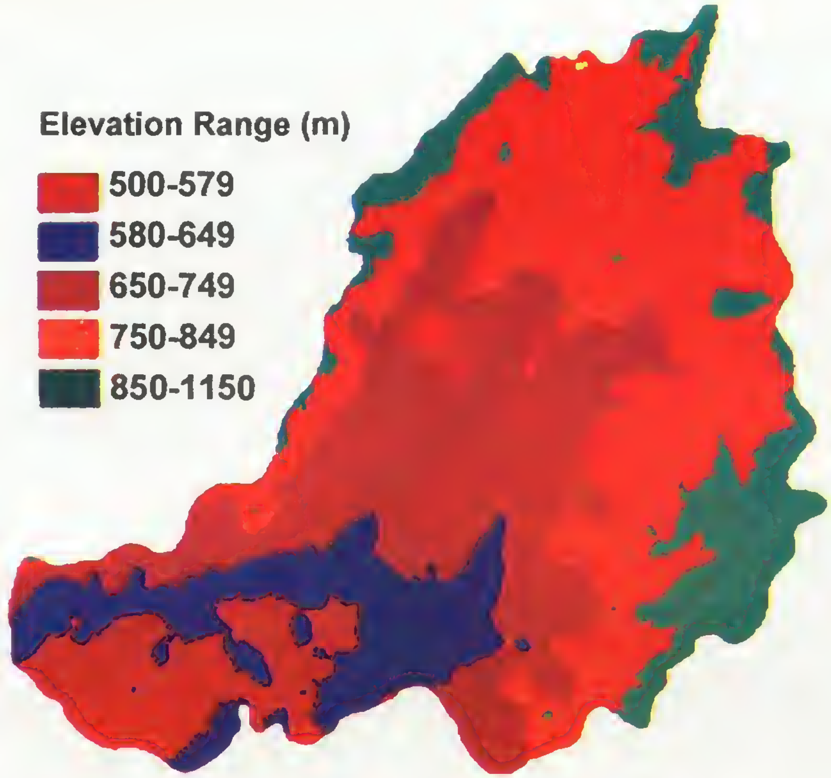


Fig.6.18Digital Elevation Map Of Sei Dam Catchment

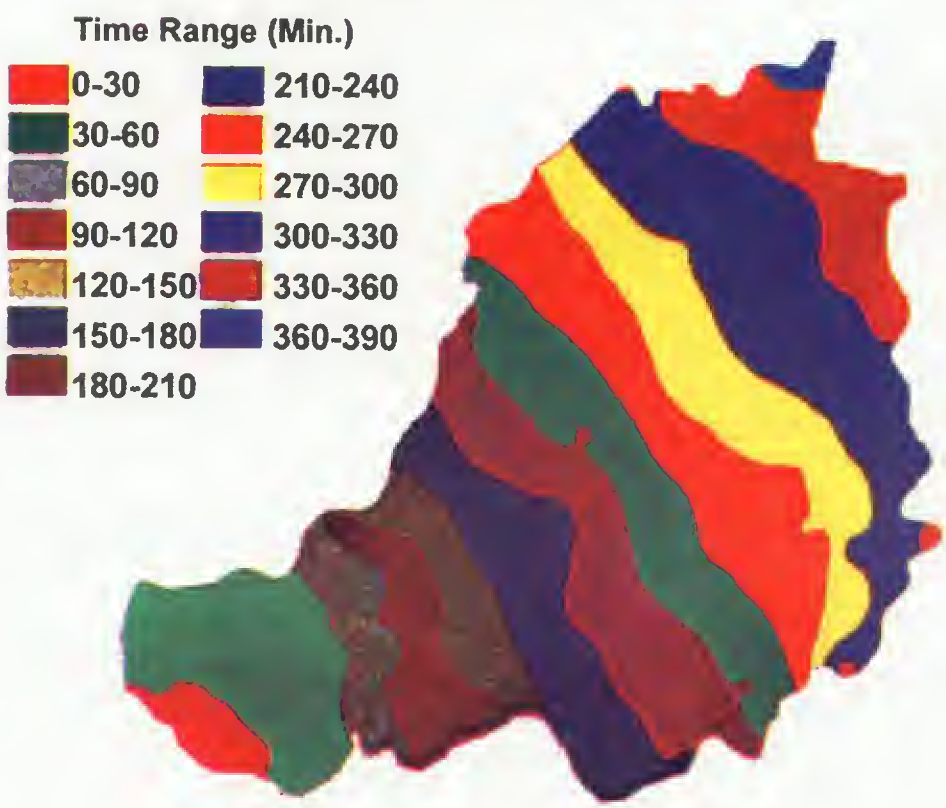
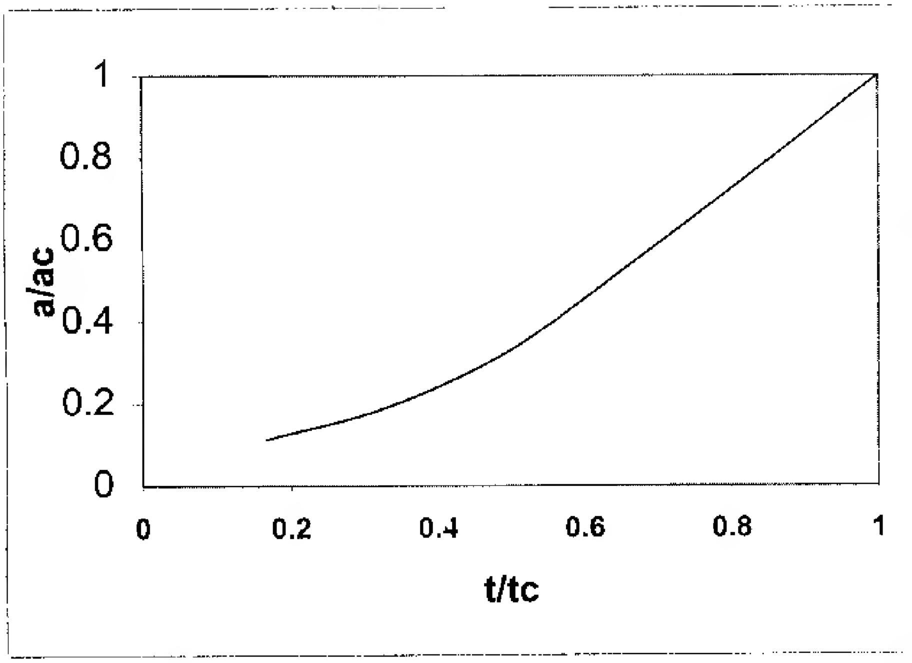


Fig.6.19Time Area Map of Sei Dam Catchment



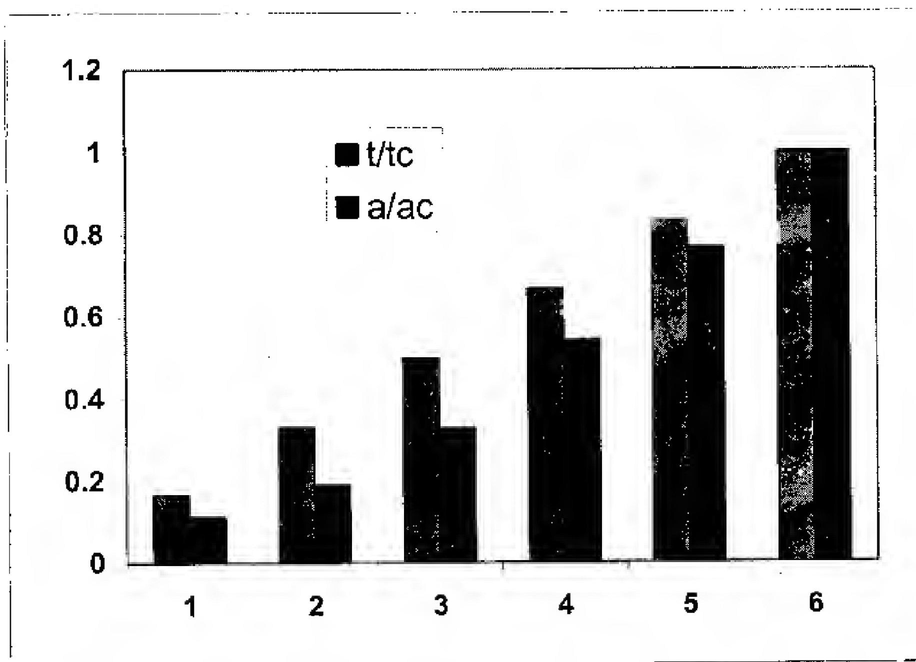
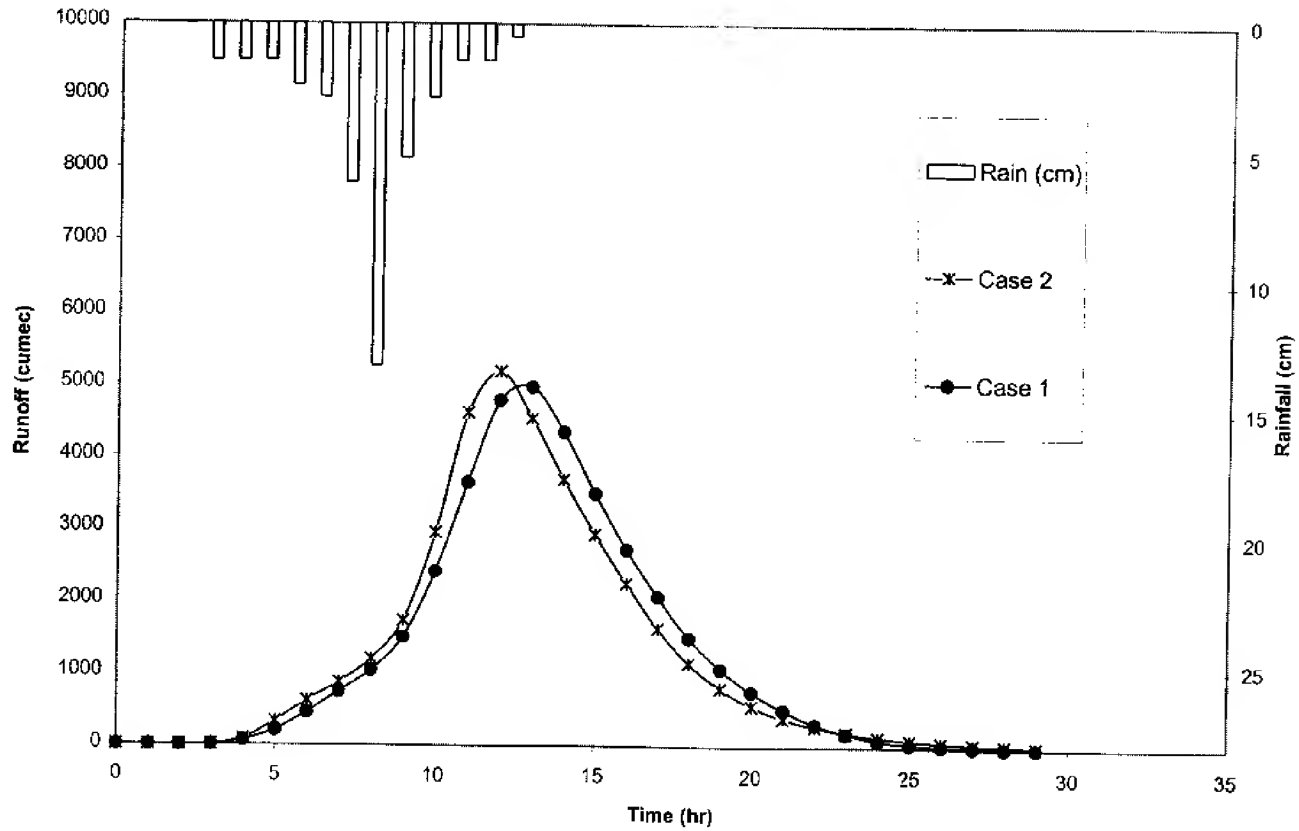


Fig.6·20 Time Area Diagram of Sei Dam Catchment

Fig. 6.21 **Rainfall-runoff simulation (Sei Dam Catchment))**



6.4 ANALYSIS FOR ALNIA DAM CATCHMENT

The drainage network map of Alnia dam catchment prepared using ILWIS is presented in Fig. 6.22. From this figure it is obtained that the catchment is of the 5th. Order. Digital Elevation Model (DEM) of this catchment has been developed and shown in Fig. 6.23. For the catchment the elevation varies from 300 to 1100 m. Table 6.10 provides the details of these geomorphological characteristics for the Alnia dam catchment. From this table it is observed that the bifurcation ration, length ratio and area ratio, which are non-dimensional characteristics are 3.82, 1.74 and 4.72 respectively for the Alnia dam catchment. These values are within the limits which have been reported in the literature.

Table 6.10. Geomorphological characteristics of Alnia dam catchment

Order	No. of streams	Average Length	Average area	Value of constants
1	235	0.788	0.466	R_b=3.82 R_l=1.74 R_a=4.72
2	48	1.715	2.59	
3	11	4.480	24.25	
4	4	6.640	97.89	
5	1	6.400	178.64	

The DEM data generated from ILWIS for Jawai dam catchment are utilized to develop isochronal map for the catchment in which the isochrone are plotted at hourly interval. A time area diagram for Jawai dam catchment has been prepared taking the contributing area on Y- axis and time of travel on X-axis. For preparing the time area diagram also the capability of ILWIS package is utilized. The time area diagram for Jawai dam catchment is shown in 6.24. In order to provide the flexibility in the interpolation of time area diagram a non-dimensional time area has been prepared taking t/tc on X-axis and a/ac (ratio of total contributing area and the catchment area) on Y-axis and shown in Fig. 6.25. The ordinate of the non-dimensional curves is used as input for the time area diagram.

The data for design storm has been prepared using the methodology discussed in the chapter 5 under section 5.4 and the value is given in table 6.11 given below:

Table 6.11 Design storm values for Alnia dam catchment

Hour	Alnia catchment
0	0.0
1	0.16
2	0.71
3	1.81
4	4.59
5	9.03
6	20.12
7	6.81
8	4.04
9	1.82
10	0.71
11	0.71
12	0.15
13	0.0

The model was run using the design storm data together with geomorphological characteristics, time area diagram and in initial parameter values. The design flood hydrographs computed for the Alnia dam catchment are shown in Fig. 6.26 considering the design storm of one bell and the corresponding values are given in table 6.12. In this figure the case 2 represent the flood hydrograph obtained from convoluting the excess rainfall hyteograph with the UH developed in the report prepared by CES Pvt. Limited.. However case 1 refers to the design flood hydrograph resulting due to application of GIUH based Clark model for the computation of design flood hydrograph. From this figure it is observed that the design flood hydrograph obtained for case 1 is higher than that of case 2. The velocity is one of the important parameter in the GIUH model. Methodology has been developed

elsewhere (Chowdhry et al.)for the computation of the velocity using the limited stage discharge observations and hydraulic characteristics of main river channel. Unfortunately for this site no historical records were available and also the information regarding the hydraulic characteristics were inadequate for evaluating the velocity. Under the circumstances reasonable values of velocity of 5.68 m/s is utilised for the condition prevailing at the time of occurrence of design flood.

Table 6.12 Design flood values for case 1 and case 2 for Alnia dam catchment

Hours	Case 2	Case 1	Hour	Case 2	Case 1
1	0	0	11	1821.011	2386.12
2	18.818	9.6	12	1124.884	1440.96
3	112.22	71.08	13	692.85	830.48
4	355.408	255.46	14	382.065	415.6
5	939.658	699.66	15	200.863	179.64
6	2096.13	1646.6	16	105.38	75.74
7	4530.944	3560.36	17	54.728	29.52
8	5550.595	5554.98	18	27.405	10.1
9	4195.765	4887.84	19	11.335	2.62
10	2896.229	3577.3	20	4.92	0.3

Fig.6·22 Drainage Network Map of Alnia Dam Catchment

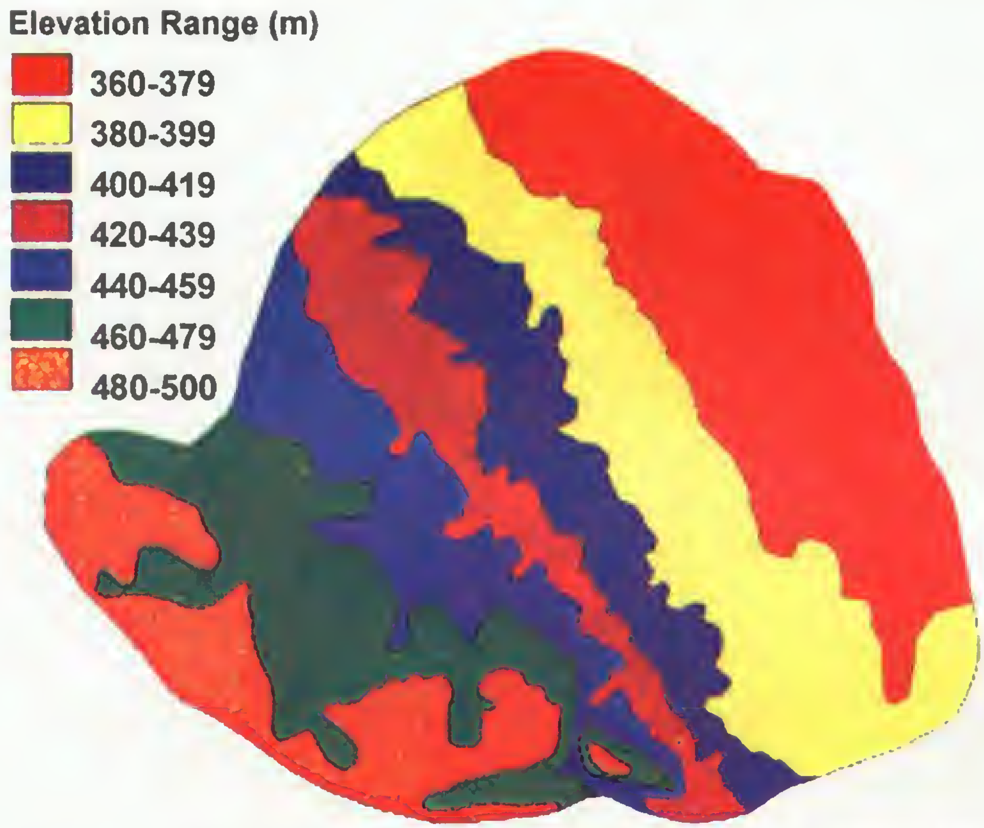


Fig.6.23 Digital Elevation Map of Alnia Dam Catchment

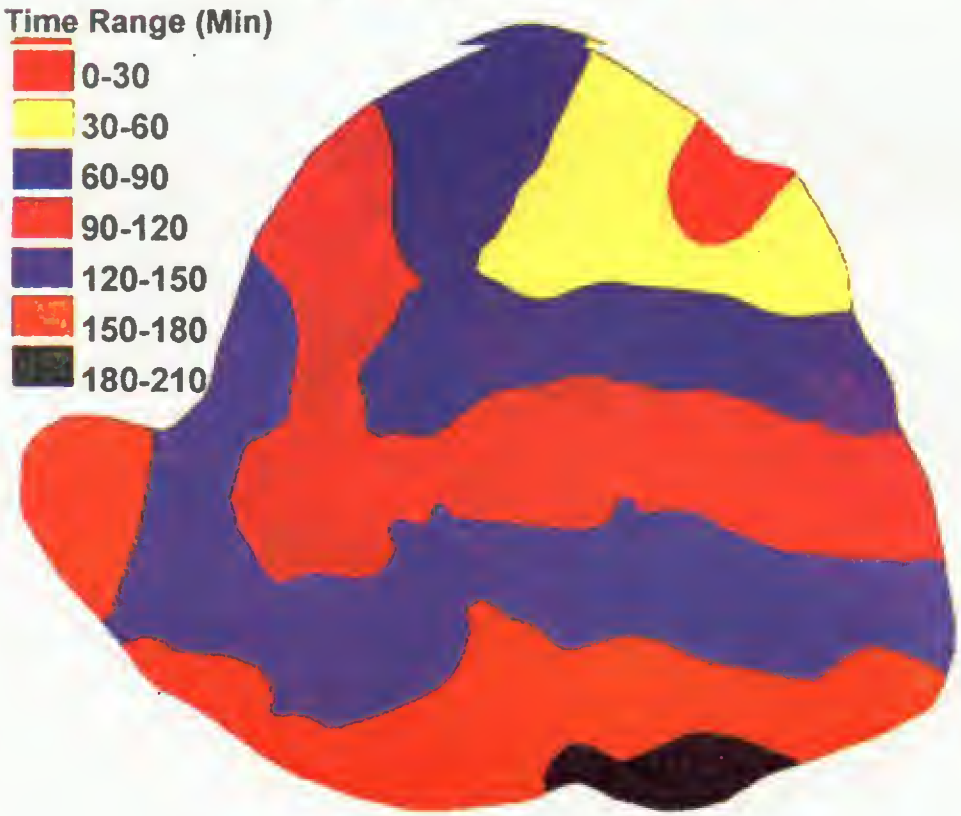
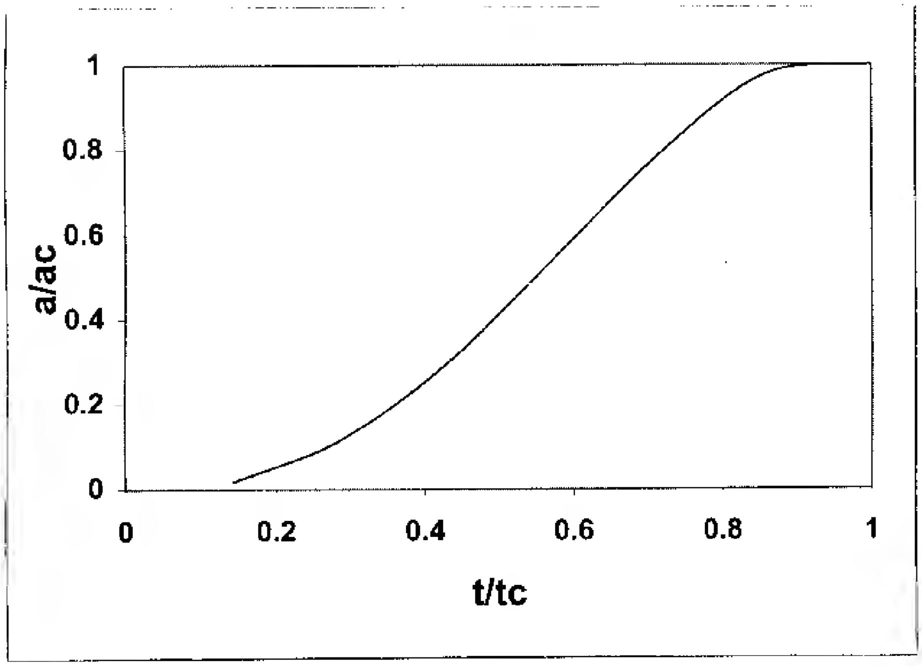


Fig.6.24 Time Area Map of Alnia Dam Catchment



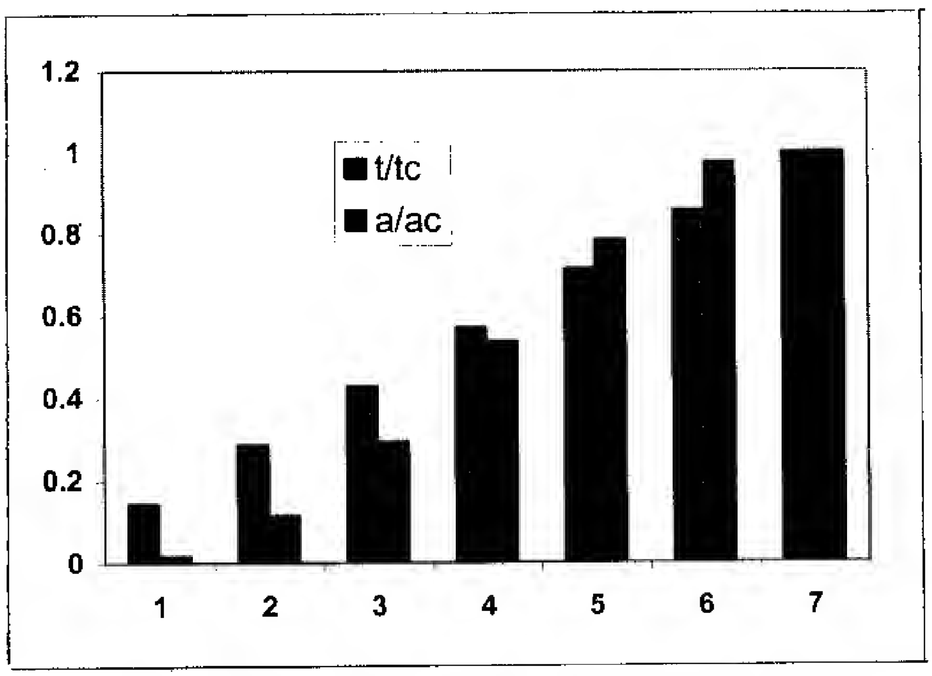
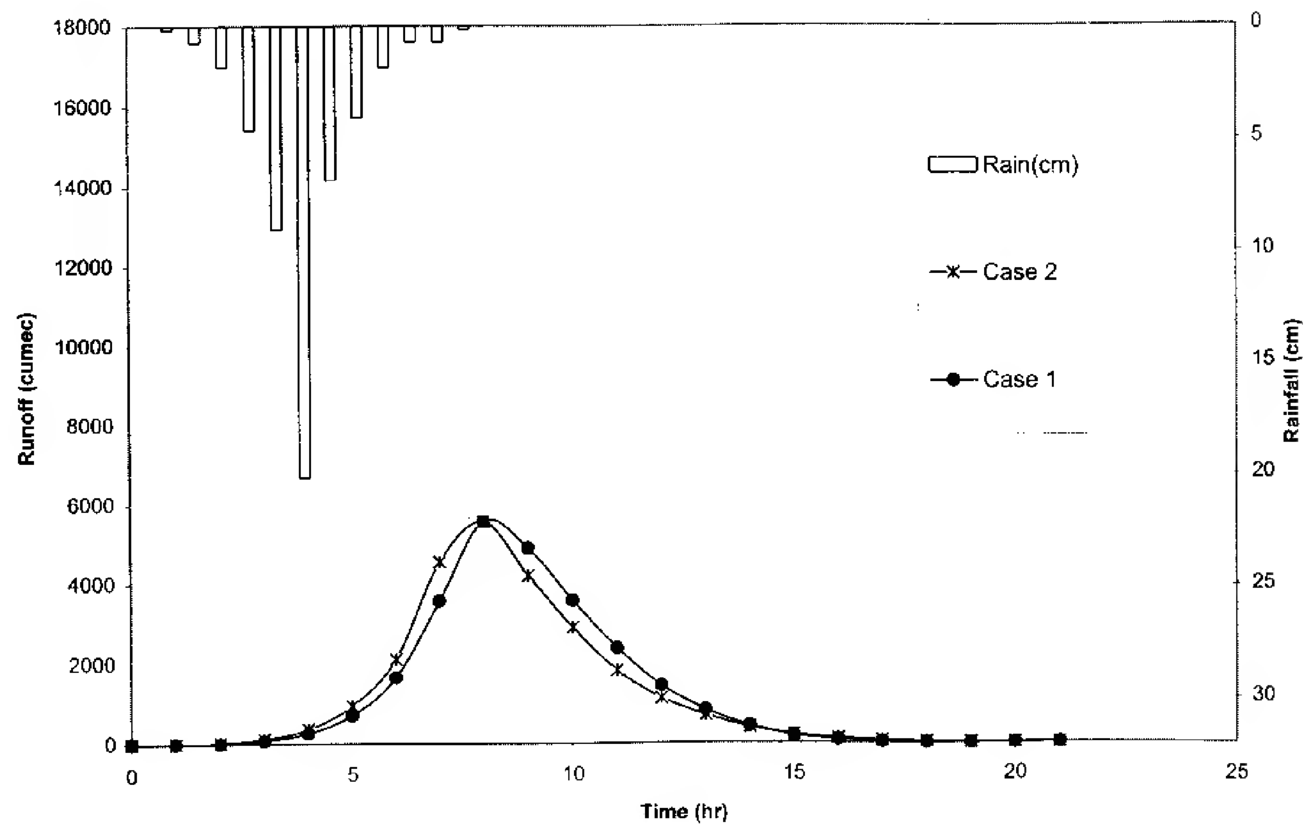
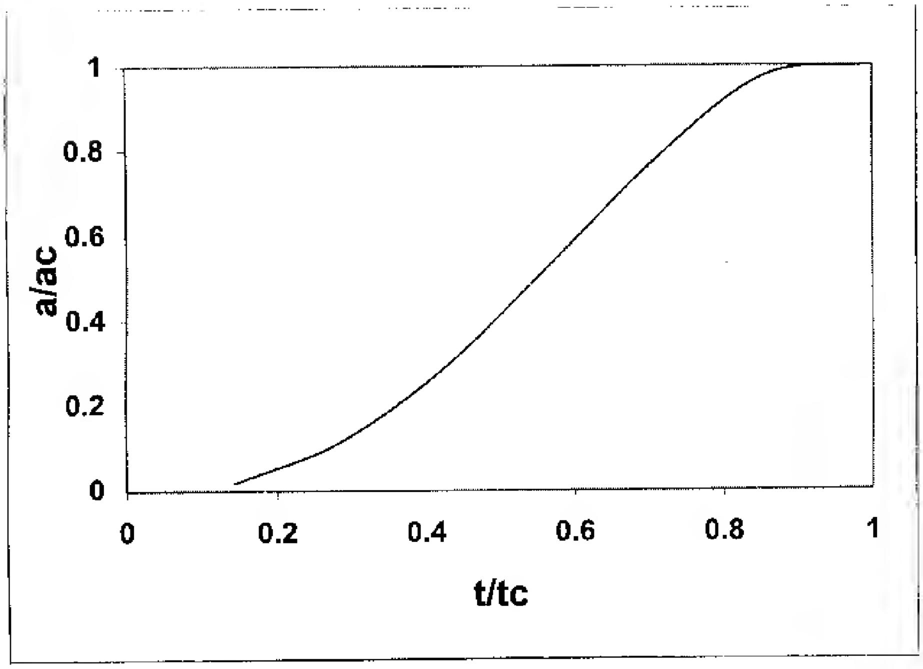


Fig.6·25Time Area Diagram of Alnia Dam Catchment

Fig. 6.26 **Rainfall-runoff simulation (Alnia Dam Catchment)**





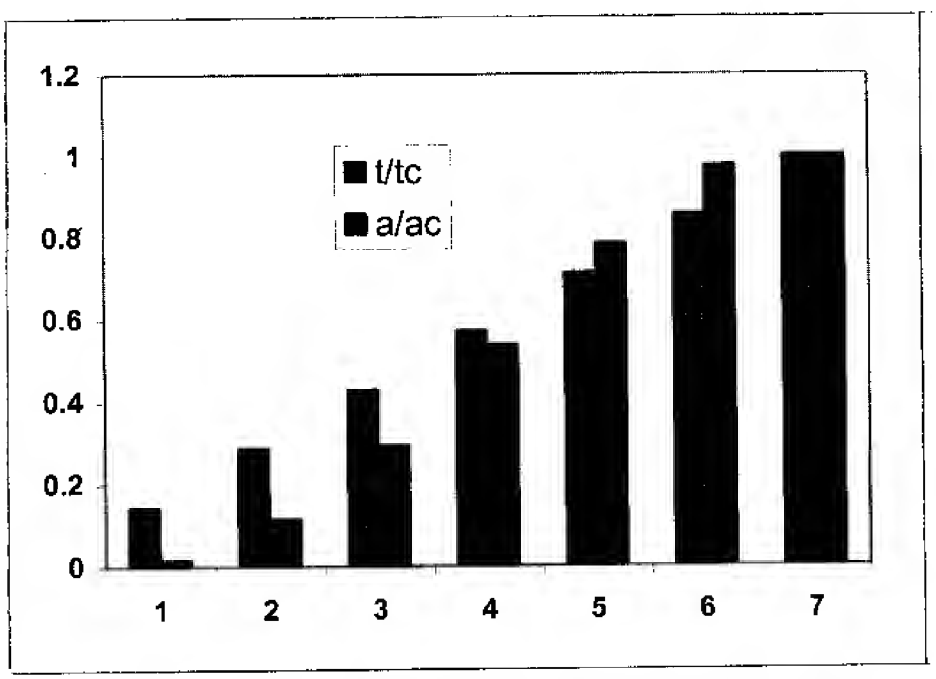
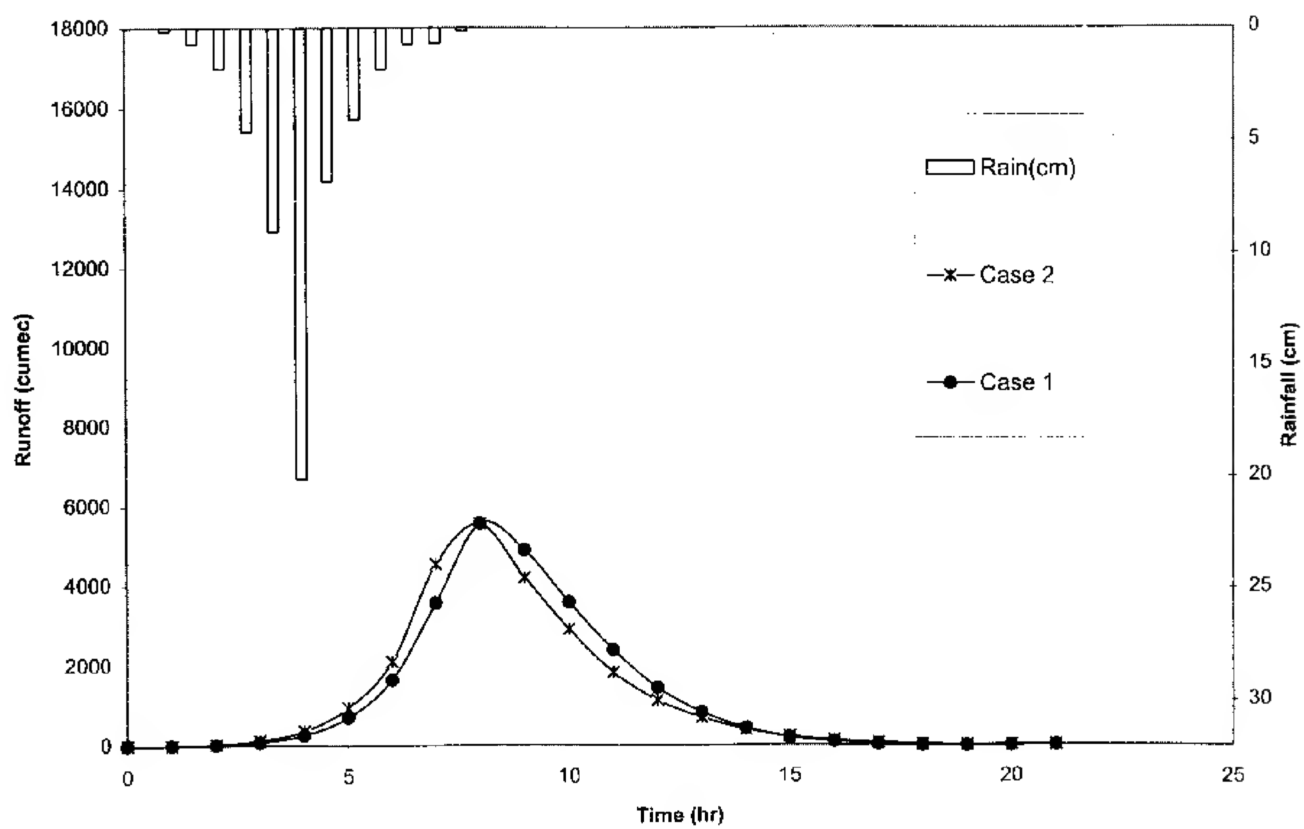


Fig.6.25Time Area Diagram of Alnia Dam Catchment

Fig. 6.26 **Rainfall-runoff simulation (Alnia Dam Catchment)**



7.0 CONCLUSION AND LIMITATIONS

In order to fulfil the objectives of this study, GIUH based approach has been applied to the four dam catchments located in Rajasthan viz. Jawai , Sei, Alnia and Gamabhiri dam catchments. The following conclusions are drawn from this study and the limitations of the study are also highlighted.

7.1 CONCLUSIONS

In this study the main objectives are as follows

- To derive the geomorphological characteristics, preparation of time area diagram etc. using ILWIS GIS software
- To derive the design storm using the different methods of critical time sequencing
- To estimate the design flood corresponding to each design storm pattern

The following conclusions are drawn from the study

- Various geomorphologic characteristics such as length of main stream, catchment area, bifurcation ratio, length ratio and area ratio have been evaluated using ILWIS GIS. The estimation of these parameters can be handled easily and more accurately using GIS system which otherwise is very tedious using manual methods.
- For the study the historical rainfall-runoff were not available to varify GIUH based Clark model approach for the four catchments considered in the study. However the design storm data was available, hence the design flood computation has been made using the methodology of GIUH based Clark model considering the different patterns of the design storm.
- For the GIUH approach the velocity is one of the important parameters. In the absence of historical data and cross-sectional details a reasonable estimates for velocity have been considering based on the indirect sources available for the basin.
- The design flood computed for various storm patterns are compared with the design flood estimates reported by CES Pvt. Ltd. Report.
- It has been found that the design flood is more sensitive to the design storm pattern and its time distribution. Hence for a reliable estimate of design flood the rainfall information pertaining to the severe most events experienced in the region may be collected and analysed to arrive at an appropriate time distribution of rainfall.

- Further study required to be taken after collecting the rainfall and runoff records at the gauging sites alongwith the short term rainfall records so as to evaluate the performance of the GIUH based Clark model methodology.
- From the study, it is observed that the GIUH and GIS based approach has potential application for the estimation of the design flood particularly for the ungauged catchments. This approach has added advantage over the conventional regional unit hydrograph technique as it dervies the time variant unit hydrograph considering the storm characteristics and avoids the cumbersome procedure of developing the regional unit hydrograph.
- Similar study needs to be carried out for a large number of catchements in order to recommend the methodology for the computation of design flood.

7.2 LIMITAIONS

- For the derivation of Clark model based GIUH approach, velocity is one of the important parameter. In order to estimate the velocity corresponding to different flood event methodology have been proposed in the earlier report brought out by NIH (Choudhry etc al., 1996). The application of this methodology requires cross section details, river characteristics etc. for the site. However for this study these information were not available, hence the estimate of the velocity has been arrived at from the indirect sources.
- The design storm and its temporal distribution have been directly adopted from the report prepared by CES for the different catchments, however critical sequencing has been tried as per the recommended practice for considering one bell, two bell etc.
- No historical rainfall-runoff records were available, due to this the methodology could not be validated for the observed events.

REFERENCES

Abrahams A.D., 1984, ' Channel Networks: A geomorphological Perspective', Water Resources Research, Vol. 20., No. 2, 161-168.

Agarwal A. and G.Das, 1987, ' Determination of Instantaneous Unit Hydrograph for Himalayan Watershed', Journal of the Institution of Engineers (India) Vol. 87, part CI 4.

Aronoff,S.,1989, Geographic Information System, WDLP publications, P.O.Box 585, Station B, Ottawa, Ontario KIP 5P7, Canada, 294 Pages.

Bhaskar,N.R.,and R.S.Devulapalli,1991,Run-off Modelling Geomorphological Instantaneous Unit Hydrograph and ARC\INFO Geographic Information System, Proc. Civil Engineering applications of remote sensing and GIS, edited by D.B.Stafford, published by ASCE.

Boufadel M.C., 1998,' Unit Hydrographs derived from the Nash model', Journal of the American Water Resources Association, Vol. 34, No.1, Februray, 1998.

Chaudhary, H.,1994,Excess Rainfall and Direct Surface runoff Modelling using Geomorphological Characteristics, TR(BR)-113 NIH, Roorkee.

Chow,V.T.,1964,Hand book of hydrology,Mc Graw Hill book Coinc, New York U.S.A.

Clark, C.O.,1945,Storage and Unit Hydrograph, Tranc. ASCE Vol.110, pp.1419-1446.

CWC, 1983,Flood Estimation Report for Upper Narmada & Tapi Subzone (Subzone 3C), Directorate of CWC, New Delhi.

DeRoo, A.P.J., Hazelhoff, L. and Burrough P.A., 1989, Soil erosion modelling using ANSWERS and GIS, Earth Surface Processes and Land forms, Vol. 14, pp 517-32.

Drayton, R.S., Wilde, B.M. and Harris, K.H.K.,1992, GIS Approach to Distributed Modelling, Hydrological process Vol.6, pp.361-368.

Gupta, V.K., Ed Wymire and C.T.Wang,1980,A Representation of in Instantaneous Unit Hydrograph from Geomorphology, Water Resources Research, 16(5), pp.855-862.

Horton,R.E. ,1932, Drainage basin characteristics, Trans. Am. Geophysics Union, Vol.13, pp.350-361.

Kirshed, M.Diana & R.L.Bras,1983, "The Linear Channel and it effect on the geomorphologic IUH", Journal of hydrology, 65, 175-202.

Lee K.T. & B.C.Yen 1997,' Geommorphology and Kinematic Wave based hydrograph derivation', Journal of Hydraulics Engineering, Vol. 123, No.1.

Lee K.T., 1998, ' Generating design hydrographs by DEM assissted geomorphic runoff simulation: a case study', Journal of the American Water Resources Association, Vol. 34, No.2, April, 1998.

Moore, I.D., Grayson, R.B., and Burch, G.T., 1987, A contour based topographic model for hydrological and ecological applications, Earth Surfaces Processes and Landforms, Vol. 1, No.4, pp 3-30.

Nash, J.E.,1957, The form of Instantaneous unit hydrograph International science hydrology, pub.45, pp.114-121.

Renaldo A. & Rodriguez-Iturbe, I., 1996, ' Geomorphological theory of the hydrological response', Hydrological Process, Vol., 10, 803-829.

Report on safety evaluation and remedial works to enhance safety status of dams, design floods at Morel, Alnia, Gambhiri and Jawai dams, Consulting Engg. Services (India) Private Limited, August, 1994.

Rodriguez-Iturbe, I. and J.B.Valdez, 1979, The geomorphologic structure of hydrology response", Water Resources Research, 15(6),1409-1420.

Rodriguez-Iturbe, I., 1993, The Geomorphological Unit Hydrograph, Chapter 3, Channel Network Hydrology, Edited by K.Beven and M.J. Kirby, John Wiley & Sons Ltd.

Ros D.D. amd M. Borga,1997,' Use of digital elevation model data for the derivation of the Geomorphological Instantaneous Unit Hydrograph, Hydrological Process, Vol. 11, 13-33.

Sorman A.U., 1995,' Estimation of peak discharge using GIUH model in Saudi Arbia, Journal of Water Resources Planning and Management, Vol. 121, No.4, July-August, 1995.

Tao T. and Kouwen, N., 1989, Remote sensing and fully distributed modelling, Journal of Water Resources Planning and Management, Vol. 115, No.6, pp 809-23.

Technical Memorandum on Hydrology of Sei dam, Irrigation Design and Research unit, Irrigation Deptt., Rajasthan, India, 1996.

Valdes, J.B., Fiallo, Y. and Rodriguez-Iturbe, I., 1979, A rainfall runoff analysis of the Geomorphologic IUH', Water Resources Research, 15(6), 1421-34.

Yen B.C. and K.T.Lee, 1997,' Unit Hydrograph derivation for ungauged watersheds by Stream order laws, Journal of Hydrologic Engineering, Vol. 2, No.1.

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